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EXPLORING THE ATMOSPHERE WITH RADIO WAVES

by H. BREMMER. 538.56:621.396:525.7

In his inaugural address as extra-mural professor of the Eindhoven Technische Hogeschool on 12th February 1960, Dr. Bremmer spoke on the ways in which study of the behaviour of radio waves has enriched our knowledge of the atmosphere. In recent years important new discoveries have been made possible by the development of space research, enabling radio transmitters to be sent out beyond the ionosphere, and by the application of highly sensitive radar methods to observations from the earth.

*With Professor Bremmer's kind consent and cooperation we print below the main contents of his address *), supplemented by some illustrations and a bibliography.*

In recent years space research has enabled us to enrich our knowledge of the physico-chemical structure of the atmosphere which, in its turn, helps to promote the advancement of space research itself. It is well known that rockets and artificial satellites are equipped with measuring instruments, and that the results of the measurements are sent back to earth in code form by a small radio transmitter in the vehicle. It is not so widely realized that the radio waves thus transmitted can also, during their travel, provide us with direct information on the space through which they pass. The behaviour of the waves is affected by this space, albeit very slightly. Radio waves transmitted from earth are similarly affected, since they too must cover a shorter or longer path through the atmosphere before reaching a receiver. In the latter case, however, it becomes extremely difficult to obtain information on the structure of the atmosphere above a height of about 400 kilometres. Unless very special installations are used, this is the maximum altitude reached by waves from a terrestrial transmitter, in so far at least as they return to earth at all after attaining a highest point and can be detected on earth. With rockets, on the other hand, radio investigations of the atmosphere can be continued beyond the 400 km limit. Projects of this nature were carried out on a limited scale during the recently concluded international geophysical year.

In the following we shall review the background of investigations in which radio waves are used to examine the structure of the atmosphere. In doing so we shall discuss both the results achieved with rockets and those obtained by measurements from the earth's surface.

The ionosphere as a hypothesis to explain the range of radio waves

Physically, radio waves are related to visible light waves. Both are propagated at a constant speed and along straight paths only when the space through which they pass is either a vacuum or perfectly homogeneous in composition. Our atmosphere, however, is only an approximation to a homogeneous space. Variations in local weather conditions are evidence that the detailed structure of the atmosphere must differ from place to place. The paths of radio waves will therefore be bound to show deviations from straight lines. The fact that these deviations can be considerable was a conclusion reached when it proved possible with certain transmitters to achieve world-wide radio communication. If radio-wave propagation were essentially rectilinear the service area of a transmitter would not extend much beyond the horizon as seen from the

*) Published (in Dutch) by J. B. Wolters, Groningen 1960.

aerial. More distant receivers lie below this horizon and cannot be reached by straight connecting lines from the transmitter. Nevertheless, reasonable reception might still be expected for some distance beyond the optical horizon, i.e. up to the first part of the shadow region, into which radio waves are diffracted to some extent — more than in the case of light waves. The depth of penetration beyond the transmitter horizon can be found mathematically. Investigations by Watson [1]*) in 1918 proved beyond doubt, however, that it was not possible in this way to explain the reception all over the earth of stations working in the wave band between 100 m and 10 m, later so widely used.

As early as 1902, Heaviside in England and Kennelly in America had concluded intuitively that the explanation for the great range of radio waves was to be sought in a non-homogeneous structure of the atmosphere. They put forward the hypothesis of a conducting layer at high altitude. The radio waves would then be able to reach any point of the earth by zigzag paths, being alternately reflected from this layer and from the earth's surface. Heaviside moreover suggested that the layer might contain charged particles formed by the ionizing action of the sun, a supposition that was later shown to be correct. Incidentally, the possible existence of such a conducting layer had already been considered in 1878 by Balfour Stewart as a likely explanation of the daily variation in the earth's magnetism. This ionized region of the atmosphere, originally called the Kennelly-Heaviside layer, is now known as the *ionosphere.*

Sounding the ionosphere

The ionosphere was at first merely a hypothesis to help explain disparate phenomena, and nothing at all was known about its height above the earth or about its other properties. It was not until 1925 that Appleton and Barnett estimated its height by an interpretation of the effect of fading, i.e. variations of the received strength of radio signals [2]. They showed that medium-wave fading in the hours of darkness could be understood by assuming that two waves reached the receiver simultaneously, one propagated along the surface of the earth, the "ground wave", and the other reflected from the ionosphere, the "sky wave". The observed fading could be explained by the interference of these two waves if the ionosphere were at a height of about 85 km. In the same year this height was first determined, more directly and accurately, by Breit and Tuve [3]). They calculated it from the observed difference in the times of arrival of the ground and sky waves. This is in fact the earliest known example of a radar experiment, since it involved an object that reflects radio waves (the ionosphere) which is not only detected but whose distance is determined. In their publication on the subject, Breit and Tuve remarked at the time: "We are hoping that such experiments will be performed by others as well as ourselves". Their hope has been fulfilled with a vengeance. More than a hundred observer stations are now daily carrying out numerous measurements on the principle indicated by Breit and Tuve. The simplest form of measurement consists in determining the time taken by a vertically transmitted signal to reach the ionosphere and return to earth. This is referred to as the echo time. Systematic "echo-sounding" of the ionosphere has become routine work, comparable with regular meteorological observations.

The echo effect mentioned depends on the wavelength or frequency used. The higher the frequency, the deeper the wave penetrates the ionosphere, and therefore the longer the echo time. Measurements showed that the ionosphere broadly consists of three successive layers extending from about 70 km to 400 km above the surface of the earth. By determining the echo time at many frequencies, and properly interpreting the results, it proved possible to lay bare the detailed structure of the ionosphere. The theory underlying the interpretation of such measurements had in fact been worked out in England by Eccles [4]) as early as 1912; it concerned the propagation of electromagnetic waves through a gas containing charged particles, i.e. through a medium similar to the ionosphere. It had been found that where different kinds of charged particles are present at the same time, namely ions and electrons, only the latter affect the way in which a radio wave is propagated. The theory showed in particular that the propagation velocity of a radio wave entering the ionosphere, called the phase velocity, must increase if the wave on its way upwards encountered increasing concentrations of electrons. As a result the originally straight path would be bent downwards, given favourable conditions, and would then return to earth. Similarly curved paths, where waves are bent downwards after reaching a highest point in an atmospheric layer, were already known in the case of acoustic waves generated by explosions and artillery gunfire. The highest point in such cases was much lower, however, being in a layer at a height of about 30 km, this layer being characterized by a high ozone content.

*) References are given at the end of this article.

But let us return to the ionosphere. It is solely because the skyward radio waves undergo an increase in their velocity of propagation that radio communications are possible over great distances. Theoretically, then, it had been reasoned that such an increase must always occur when a wave enters a medium containing charged particles. It remained to verify this conclusion by a laboratory experiment. The first to do so was Van der Pol, who gave a full account of his methods in his thesis in 1920 [5]). A general understanding of the mechanism of radio transmission via the ionosphere thus existed five years before the separate ionospheric layers were first directly observed in 1925.

A further advance was made in 1930 when W. de Groot [6]) gave a mathematical method for directly determining the electron concentrations in the layers from the observed frequency dependence of the ionospheric echo times. In this way it was found that in the best-known layers (called D, E and F layers, in ascending order) the number of electrons per cubic centimetre was of the order of 10^3, 10^5 and 10^6, respectively. De Groot pointed out that it was only possible with this method to investigate the lowest part of each layer, i.e. the part below the level where the electron concentration is a maximum. Now, since the advent of rocket missiles, data can be collected on each layer through which the rocket passes [7]). This is done by measuring the frequency change — the so-called Doppler effect — of the radio signal sent back to earth by a small transmitter on board the rocket. Here the Doppler effect depends on the rocket's speed and on the local velocity of the radio wave; the latter depends in its turn on the electron concentrations near the rocket. Since the speed and course of the rocket are known, the electron density at all altitudes of the rocket can be determined directly from the variation of the Doppler effect. These new measurements broadly confirm the picture of the ionospheric layers earlier arrived at with the aid of echo sounding. Faith in the old results was so great that one commentator, discussing the confirmation provided by the rocket tests, said ironically: "This simply means to me that the rockets have in fact got through to the ionosphere". Nevertheless, the correspondence is not perfect; in particular it now appears that the layers of the ionosphere are not so clearly separated as they were formerly supposed to be. For example, the minimum of the electron density at the transition from the E to the F layer is extremely shallow or even imperceptible.

The space above about 400 km

Until a year ago no detailed picture was known of the electron density above the middle of the F layer, which is the region above a height of about 400 km. More information has now been made available on this region by new radar experiments at a wavelength around 7 m, performed by Bowles [8]) of the National Bureau of Standards. A wave as short as this passes almost unhindered through the ionosphere, but reception is still possible, albeit with a great deal of trouble, of the extremely weak signal which is sent back to earth by the wave on its way up to very great altitudes. This weak signal results from the fact that the individual electrons in the upper atmosphere absorb energy from the oncoming radio wave and then scatter this energy in all directions.

Part of the scattered energy then returns to earth. The returning energy being proportional to the electron concentration, the latter can therefore be determined from the signal received. A measurement is made of the time variation of this signal shortly after the primary signal is sent out. In the first moments, only the contributions produced in the lowest regions of the ionosphere will be observed, these being the earliest to return. Thereafter the intensity is determined by the electron concentrations at increasingly higher levels.

To obtain a measurable signal strength in this experiment, a very powerful transmitter and a large aerial system are needed. These of course involve considerable costs, but the costs are very much lower than would be entailed if an artificial earth satellite were used to acquire the same data. The provisional results show that the electron density above the F layer decreases very gradually and that there are thus no further layers of high electron concentration. Future observations with the aid of artificial satellites will undoubtedly provide supplementary information.

Another important fact has been established by much simpler observations, viz. that up to very great heights a minimum concentration prevails of about 500 electrons per cm^3, or at least that there are always local regions present with this electron concentration. This has been inferred in particular from observations of the phenomena known as "whistlers". These are electrical disturbances which are generated by thunderstorms and are propagated from their terrestrial source along a line of force of the earth's magnetic field that extends far into the atmosphere; the path of propagation along this line of force shows a horseshoe bend, finally returning to earth somewhere in the opposite hemisphere (*fig. 1*).

From such observations Morgan and Allcock [9])

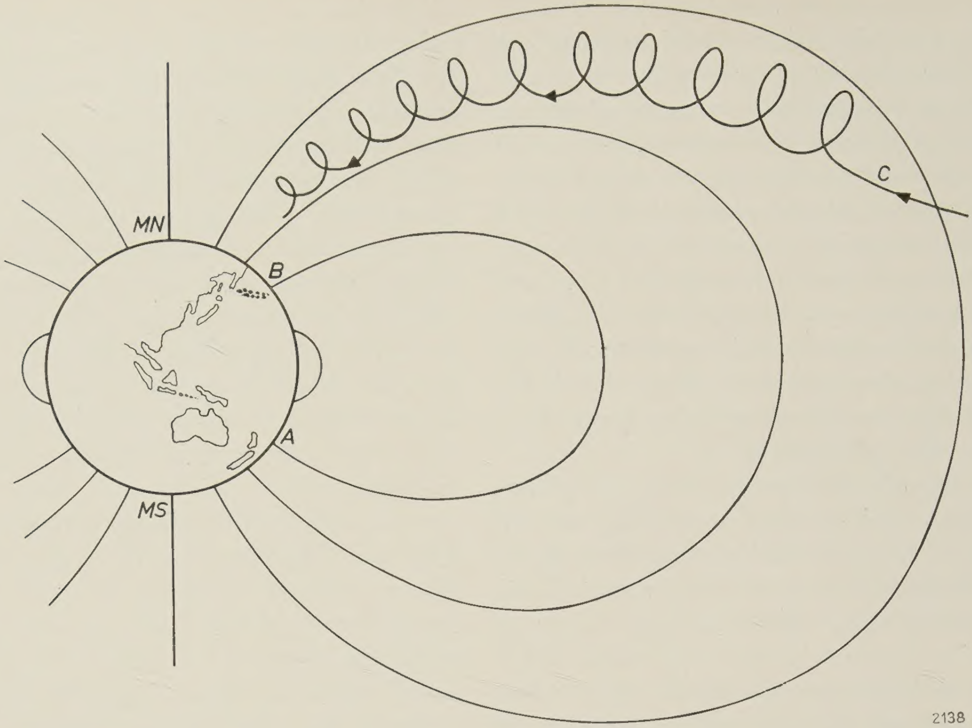

Fig. 1. The earth, with magnetic poles *MN* and *MS*, showing a number of magnetic lines of force.

Electrical disturbances generated at *A* (e.g. by a thunderstorm) are propagated along a line of force of the earth's magnetic field and reach a point *B* in the other hemisphere. At *B* they may give rise to a "whistler". The disturbance can travel to and fro many times along the line of force *AB*.

When a charged particle — emitted by the sun — approaches point *C* in the transitional zone, where it first comes under an appreciable influence of the earth's magnetic field, it starts to describe a helical path around a line of force. Upon arrival in the lower atmosphere such particles may produce auroral effects. The paths of the lines of force indicate that the charged particles mainly enter in a region forming a ring around the magnetic north and south poles (aurora borealis and aurora australis).

recorded a case in 1955 where disturbances of this nature repeatedly made the long journey to and fro between Wellington in New Zealand and Unalaska on the Aleutian Islands. On their way they reached at their farthest point a distance of more than 20 000 km from the earth. Whistlers also contain frequencies in the audio range, which are heard in the receiver as a short fluting tone of descending pitch, hence their name. Another related kind of whistling atmospherics appears to originate in the upper atmosphere, probably as a result of fast-moving currents of ionized particles [10]): the sound heard resembles the twittering of birds, and has therefore been termed "dawn chorus". All these disturbances roughly follow a line of force of the earth's magnetic field. The saying that the traveller from afar has much to relate is certainly apt in their case. The properties of a whistler depend on the electrons it has encountered on its journey. Analysis of the incoming signal reveals in particular that the long journey is possible only if it is made through regions where the electronic concentration is at least of the order of the above-mentioned value of 500 electrons per cm^3. An important effect in this connection is that the electrons tend to arrange themselves in "filaments" along the lines of force of the earth's magnetic field.

The presence, formerly unsuspected, of relatively high electron densities up to very great heights above the earth (see *fig. 2a*) has been confirmed in other ways. In the first place, it agrees with the recordings of a positive-ion detector on board Sputnik III [11]). The concentration of positive ions is an indication of the presence at the same time of a concentration of negatively charged electrons. Further confirmation has come from a recent study by Siedentopf, Behr and Elsässer of the brightness and polarization of the zodiacal light [12]). In studying this phenomenon it is necessary to assume that the polarization effects are due solely to electrons, leaving out of consideration any effects that may be due to the dust particles also present. This means that the electron densities thus calculated are maximum values. Thus, from observations of three entirely distinct phenomena it has been made plausible that a minimum density of about 500 electrons per cm^3 exists up to very great distances from the earth.

The investigations mentioned hitherto enabled the electron concentrations to be inferred up to a certain height above the earth. It is also possible, however, to determine by direct means the total number of electrons contained in a column extending from the earth's surface far into cosmic space. For this purpose use is made of the recent radar experiments, where a radio signal is reflected from the moon. From the fading shown by the returned signal one can find the number of electrons contained in a narrow column reaching from the earth to the moon. Measurements by Evans [13]) and by Bauer and Daniels [14]) have shown that this number amounts to about 20×10^{12} electrons in a column of 1 cm² cross-section. Suppose for a moment that the prevailing electron density was 500 per cm³ over the whole distance from the earth to the moon (380 000 km); the column would then contain 19×10^{12} electrons. This of course leaves hardly any margin for the much greater electron density that must in reality be present in the column at the position of the E and F layers: the necessary margin exists, however, if we assume an electron density outside these layers of, say, 400 per cm³, which is of the same order of magnitude as the 500 per cm³ mentioned above.

The results obtained indicate that the total number of electrons above the "middle" of the F layer is 3 to 5 times greater than the known number of electrons below that level (by "middle" we mean here the level of maximum electron concentration, denoted by M in fig. 2a). With a similar method [15]) the total number of electrons can be determined between the earth and an artificial satellite in orbit at a specific height. This number can also be calculated from the recorded moment at which signals transmitted by such a satellite are last received after the satellite has disappeared beyond the horizon [16]). The same applies to the moment at which the signals are first picked up again when the satellite reappears above the horizon. In this way, with the aid of Sputnik II, it was established that the electron density in the upper half of the F layer declines much more gradually than it increases in the lower half upwards. This is in agreement with the measurements performed by Bowles [8]).

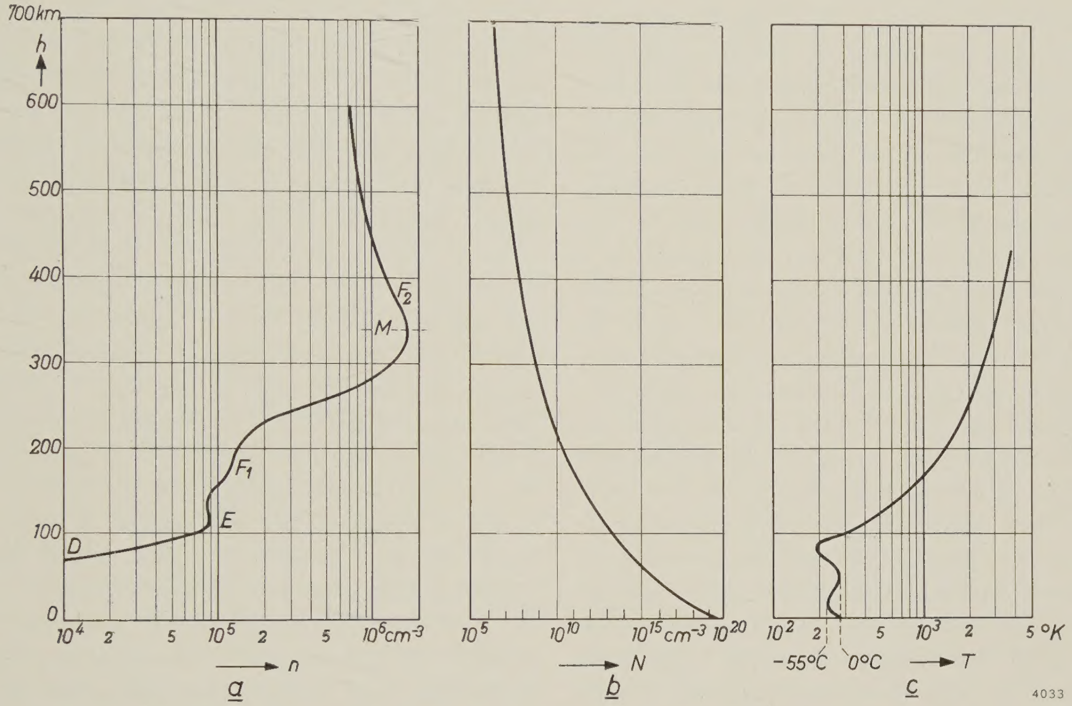

Fig. 2. The graphs show respectively as a function of height h above the earth's surface:
a) the number of electrons n per cm³,
b) the number of particles N per cm³ (here mainly molecules in the lower regions and mainly atoms at higher altitudes),
c) the temperature T (in °K, but also in °C at lower altitudes).
In (a) the letters D, E, F_1 and F_2 denote the correspondingly named layers of the ionosphere; the greatest electron concentration is found at the level M (the "middle" of the F_2 layer). The change with height in the concentration of the electrons varies with the relative position of the sun and with the sun's activity. The curve shown is representative of a state during the day, when the F layer can be divided into an F_1 and an F_2 layer.

Density and temperature of the atmosphere as a function of height

There is thus a great deal of information available for studying the concentrations of electrons in the atmosphere. Being established with a relatively high degree of certainty, the data at our disposal represent an excellent starting point for building up a picture of the physical conditions existing in the space around our planet. In the first place, once we know the distribution of the electron concentrations in a particular layer, we can deduce from that distribution the molecular density and the temperature prevailing near the middle of the layer. This is possible because the formation of the layer partly depends on the absorption of ionizing radiation from the sun by atmospheric molecules or atoms. Factors thereby involved are the average concentration of these uncharged particles, and also the change which their concentration undergoes with changing height as a result of temperature. It has been found in this way that the gas density at a height of 100 km is roughly a million times smaller than near the earth's surface (fig. 2*b*), whilst the temperature at that height must be roughly equal to room temperature (fig. 2*c*). This does not imply that one would feel comfortably warm in this region, but simply that the molecular velocities of thermal agitation are just about the same there as in the air in which we live. Above the 100 km level, however, there must be an increase in temperature, otherwise the density of the uncharged gas atoms would decrease upwards much faster than it actually does.

Apart from the results obtained with radio waves, there are other indications that the decrease in the density of the air above about 100 km is so slow that it must necessarily be accompanied by a rise in temperature. These indications have come from air-pressure measurements aboard rockets and also from observations of auroral effects and of the light in the night sky [17]). As regards the latter, it should be recalled that on a clear, moonless night only about 30% of the faint light from the sky originates from the stars, directly and by scattering in the atmosphere, whereas some 40% is due directly to luminous gases in the upper atmosphere (the other 30% is scattered light due to other causes). From observations of this light we can thus estimate the density and temperature of the gases up to a height of about 1000 km.

The rise in temperature above 100 km is quite understandable, since the extremely thin atmospheric gas must finally make the transition to the so-called *interplanetary gas* of outer space. It is known that this gas has a very high temperature, and moreover it consists almost entirely of the simplest charged particles, namely protons and electrons. It is thought that the high velocities of these particles, corresponding to their high temperature, are such as to overcome the attraction of the planets, though not of the sun. The sun itself is probably the chief source of interplanetary gas, which might be regarded as a continuation of the rarefied and very hot gas of corona that envelops the sun.

Let us now consider the general picture of the atmosphere above about 500 km, as pieced together from theoretical insight and from the scarce data provided by rocket flights. The chemical composition of the air up to roughly 200 km differs only very slightly from that of the air we breathe, but above that height the atomically dissociated oxygen and nitrogen are gradually superseded by the much lighter atomic hydrogen. Above a height of the order of 1000 km the density has diminished to such an extent that the chance of gas particles meeting one another is very remote indeed and there are virtually no more interaction processes between the atoms, ions and electrons still present. Consequently the concentration of the uncharged atoms is henceforth entirely governed by the force of gravity, so that at very great heights only the lightest gas is found — hydrogen. At a distance of three earth radii, i.e. at a height of about 20 000 km, the (uncharged) hydrogen atoms have sufficient velocity, in view of the temperatures prevailing there (~1200 °C), to overcome the very weak gravitational pull of the earth. As far as the (electrically charged) ions and electrons are concerned, however, the effect of the earth's magnetic field, and the forces associated with it, are more important than the force of gravity. These particles remain much longer within the earth's sphere of influence, so that finally only the lightest, charged particles remain, i.e. protons and electrons. The latter are found there in the concentration referred to of the order of 500 particles per cm^3. For the sake of completeness it may be mentioned that Geiger counters carried by rockets have revealed the existence of at least two zones, called Van Allen zones, of highly intensive radioactive radiation [18]), whose maxima are situated at heights of about 3000 and 16 000 km above the earth's surface. The radiation is probably due mainly to high-speed electrons originating from the sun.

Transition of the atmosphere to interplanetary gas

The model described here seems to point to a very slow transition from the increasingly rarefied upper

atmosphere to the region of interplanetary gas, which, according to Siedentopf and co-workers [12]), also possesses near the earth a density of the order of 500 electrons per cm^3. It should be remembered, however, that this gas does *not* take part in the daily rotation of the earth, whereas the air near the earth is carried around in its entirety. With increasing height, then, the air ought to be gradually less firmly bound to the earth. This, however, raises a theoretical difficulty. If the earth's magnetic field decreases with increasing distance at the same rate as it does near the earth, one can calculate the viscous forces due to electromagnetic effects that correspond to a minimum density of 500 electrons per cm^3. It is found that these forces are so strong as to suggest that the atmospheric air down to regions close to the earth is coupled more with the interplanetary gas, which does not move with the earth, than to the rotation of the earth. The movement of the air that does not entirely rotate with the earth should manifest itself in a prevailing east wind, and this should already be observable at a height of 100 km above the earth. This is certainly not the case, however. The difficulty disappears if there exists a transition zone in which the earth's magnetic field declines so rapidly as to be negligible beyond that zone. The form of the magnetic lines of force that fits this model is then such that the protons and electrons near the transition zone can only penetrate through it with great difficulty; the possibility of limited penetration from outside is then essential to explain auroral effects. The particles outside the transition zone are thus more or less isolated from those inside it. This makes it possible for all particles inside to rotate with the earth, whilst those outside it are coupled with the interplanetary gas. The transition zone, which may perhaps coincide with the central part of the outer Van Allen zone, at a distance of roughly 16 000 km, then acts as a natural boundary of the earth's atmosphere, at a level where it consists almost entirely of protons and electrons.

The transition zone thus screens the earth's magnetic field, and this implies theoretically that it must at the same time be the carrier of electric currents. It was for this reason that the existence of such a zone was first postulated, for these currents are the simplest explanation of phenomena connected with the disturbances of the earth's magnetism known as "magnetic storms". Since 1923 the relevant theory has been worked out in particular by Chapman, Ferraro and Martyn [19]). They have shown that a transitional layer must necessarily be formed whenever a stream of charged particles (thrown off by the sun) enters a magnetic field that initially decreases very gradually as a function of the distance to the earth. Any stream of particles will then tend to distort the latter field into a field of the type considered above. The regular production of such streams by solar eruptions accordingly maintains this type of field with a transitional layer. The most recent observations indicate that the transitional layer may be identical with a boundary region in which the earth's magnetic field loses its regular and slowly varying structure — in other words, the transitional layer represents the outermost zone in which the field still possesses a distinctly stable component.

Ionospheric winds

We have just said that there are no indications of a prevailing east wind at a height of 100 km. This appears from a variety of investigations, again using radio waves reflected from the ionosphere [20]). The fading of these waves may be studied. Because of irregularities in the structure of the ionosphere, the moments at which the signal from a given transmitter is received most strongly by several receivers in each other's vicinity do not coincide. From the time differences recorded one can determine the direction and the strength of the wind prevailing at ionospheric altitudes. No prevailing east wind is observed, but winds of considerable velocities do occur at a height of 100 km. Wind velocities of the order of 50 metres per second, i.e. 180 km/h, appear to be quite normal. Such hurricanes should not be imagined too dramatically, however, for the air density there is about a million times less than at the earth's surface. The mass of air displaced per unit time at such high velocities is therefore very small — too small, for example, to turn a rocket noticeably off course.

Radar observation of meteors

In recent years the ionospheric winds in the E layer have been very systematically studied by radar observations of meteors [21]). In spite of its rarefication, the air at a height of 115 km is still dense enough to make meteors entering the atmosphere at that level white hot. The resultant vaporization is so intense that most meteors have completely evaporated before they can drop to an altitude of about 80 km. The heating process is accompanied by the ionization of atoms from the meteor, and a temporary trail of strongly ionized air is left behind. The trail may remain intact for as long as ten seconds, after which it dissipates as a result of diffusion. For a short time, then, there exists a cylindrical, expanding column in which electrons occur at a

concentration often ten-thousand times greater than in the surrounding air of the ionosphere. Radar waves are reflected from a short-lived column of this kind, and meteors detected in this way occur at an average rate of one per second, against one every seven minutes observable by the naked eye. With a telescope almost as many meteors can be observed as with radar, but the latter has the advantage of being just as useful during the day as in the hours of darkness. These investigations can therefore be carried out both by day and night.

The study of meteors by radar has attracted considerable interest in the last ten years. Information can also be gathered in this way on air currents at high altitudes, since the ionized trails left behind by meteors are blown along during their brief existence by local winds. The component of this wind motion in the direction of observation can be derived from the Doppler shift in the frequency of the reflected waves. Statistical analysis of the wind components measured on large numbers of meteors makes it possible to calculate the force and direction of the prevailing wind in a given region of the ionosphere. These calculations confirm the above-mentioned wind velocities of the order of 50 m/s. The most direct indication of these wind velocities, however, is found from observations of the "luminous clouds" that are sometimes seen at high altitudes a few hours after sunset or before sunrise [22]).

Atmospheric tides

The wind phenomena discussed here share to some extent the random nature of the winds near the earth's surface, which are governed by meteorological conditions. A large contribution to the ionospheric winds, however, is attributable to solar and lunar tidal forces. We are most familiar with tidal forces from the periodic alternation of ebb and flow in the seas. The same forces act on the air of our atmosphere, but they are much less noticeable. Our position as observers in relation to the atmosphere might be compared with that of someone trying to study sea tides from the bottom of the sea. This comparison suggests that the atmospheric tidal effects are perhaps much more pronounced at greater altitudes. A periodic vertical movement of air as a result of tides might, for example, manifest itself as periodic variations in the height of each ionospheric layer. In fact, echo-time measurements revealed for the first time in 1939 that these layers do indeed show a periodic rise and fall. In that year Appleton and Weekes [23]) found that the height of the E layer undergoes small variations of the order of 2 km, which are directly related to the phase of the moon.

Vertical tidal movements in the air, like those in the sea, are not conceivable without accompanying horizontal movements. One might therefore suppose tidal effects to be at the back of the wind phenomena detected by radar observations of meteors. Tidal winds do in fact appear to exist in the ionosphere. The effects due to the sun and moon separately can be kept distinct in this connection inasmuch as their respective contributions vary with the position of the sun and the moon. The tidal wind caused by the sun shows a highly regular pattern; at an altitude of 85 km in the northern hemisphere it may be described broadly as a wind, constantly changing in direction, and veering from the west in the morning and evening at half past eight local time; its maximum force is roughly 70 km/h.

Tidal winds as strong as this are out of the question near the earth's surface, where the prevailing winds are governed by meteorological conditions. Still, a tidal contribution does exist on the earth, albeit a very slight one. It can be found from the averages of barometric readings taken over a long period at times when either the sun or the moon is at the same position in the sky. By taking average readings the influences of incidental and constantly changing meteorological conditions are eliminated. In this way one finds a small tidal effect attributable to the sun, and further a 16 times smaller effect due to the moon. From the local distribution of these accurately determined statistical averages the associated, very slight tidal contribution to the wind on the earth's surface can later be calculated [24]). The results show that, on the equator, the tidal action of the *sun* superimposes on the meteorological winds an extra east or west wind which has a maximum force of less than one kilometre per hour. In higher latitudes this weak tidal component constantly changes direction, just as it does in the ionosphere. The even weaker atmospheric tidal effects due to the *moon* [25]) indicate that our faithful satellite has no significant influence on the distribution of the air in our atmosphere.

A comparison of the tidal winds blowing at velocities up to 70 km/h at a height of 85 km with the tidal wind of about 1 km/h near the earth might suggest that the tidal effects are generated primarily in the higher layers of the atmosphere. This, however, is by no means the case. If we take into account the rarefication of the upper air, we find that the energy transmitted by the tidal forces to unit volume of air is much greater near the earth's surface than in the ionosphere. The energy taken up near the earth, however, gradually moves upwards, thereby

appreciably strengthening the tidal wind due to the sun, at least above a height of about 30 km.

It was for a long time puzzling that the sun's contribution to the atmospheric tides should be so much greater than the moon's. This seemed to conflict with the elementary theory according to which the moon's contribution should be $2\frac{1}{2}$ times greater than that of the sun, a deduction based on the relative masses of the sun and moon and their distances from the earth. As regards the ocean tides, the moon is in fact the more effective of the two. We know that the times of high water along the coasts are almost entirely governed by the relative position of the moon; the weaker effect of the sun is responsible for the spring tides shortly after full moon and new moon. The fact that the sun plays the major part in the atmospheric tides was noticed by Laplace one-and-a-half centuries ago. In 1882 Kelvin suggested that a resonance effect might be involved. He conceived that the atmosphere might easily enter into an oscillatory movement whose period, for one reason or another, may well be close to the twelve-hour period governing the solar tides. On the other hand, the corresponding period of nearly thirteen hours for the lunar tides would not be close to a resonance period of the atmosphere. It was not until 1936 that it was first shown by Pekeris [26]) that among the resonance periods of the atmosphere there is in fact one of about twelve hours.

The duration of this resonance period, which has such an important bearing on the atmospheric tides, is very closely related to the temperature distribution in the upper levels of the atmosphere [27]). It would be quite different if the temperature of the air decreased upwards continuously. We know that the temperature has a minimum value of about —55 °C at an average height of 10 km, after which it rises and at about 50 km reaches an average value near 0 °C (fig. 2*c*). It then drops again until, at a height of roughly 85 km, it reaches a minimum value of about —80 °C. This is where the above-mentioned temperature rise begins, which continues right on up to the transitional zone bounding the atmosphere. It is the presence of two layers in which the temperature drops with increasing height that involves a resonance period of roughly twelve hours. The theory of resonance also indicates that the solar tidal wind at a height of 75 km must be about 100 times stronger than near the earth, and moreover that above 30 km it must blow in the opposite direction. This is entirely in agreement with observations of wind directions in the ionosphere, and serves to strengthen confidence in the theory.

In broad lines it can be said that theory and observation together have produced a satisfactory picture of the atmospheric tides in the lower atmosphere. According to the so-called dynamo theory [28]) the ionospheric tidal winds are partly responsible for the systems of electric eddy currents in the ionosphere; this ties up reasonably well with what can be deduced about these currents from the study of the earth's magnetism. Radar observations of meteors further indicate that above 100 km the tidal winds are rapidly attenuated, apparently because the tidal waves are strongly damped when they enter this region. This can be explained by the effects of viscosity and thermal conduction that first become effective there. Future investigations will undoubtedly deal in greater detail with the attenuation of tidal effects at high altitudes.

Concluding remarks

The reader may now be wondering whether the investigations discussed are of any technical importance apart from their purely scientific interest. It should be remembered that research with the aid of radio waves can provide fresh insight into the uses of radio waves as a means of communication. In this connection it may be recalled how the familiar reflection and scattering of radio waves from ionized clouds prompted the American Thaler to turn this phenomenon to use for tracing guided missiles and nuclear explosions [29]), both of which give rise to such clouds.

I have tried to show in this survey how very valuable a tool radio has proved to be for exploring the mysteries of our atmosphere. In the skies above us there are many long-unsuspected phenomena at work, which are only now gradually yielding up their secrets. For the physicist it is a fascinating field of research, involving as it does such diverse branches of study as radiation theory and plasma physics, which are particularly important in the upper layers, the physico-chemical theories underlying the ionization and energy-exchange processes between the particles in the somewhat lower layers, aerodynamic and electrodynamic theories, which apply to the air currents above 100 km, and classical mechanics, which govern the tidal effects in the lowest layers. No one is entirely indifferent to the achievement of human ingenuity in establishing radio communication all over the earth, and it is natural that we strive to understand more of the mechanisms that make that communication possible. One final comment may not be out of place in this connection. It is remarkable how the subtlest-seeming phenomena play a fundamental role in radio telecommunications. For example, the highly

rarefied gas of the ionospheric F layer has a lower density than the so-called vacuum in the best high-vacuum pumps; nevertheless, it is this gas, through the thinly distributed electrons it contains, that enables us to listen to a station at the other end of the earth.

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Summary. The substance is reproduced of the address delivered by the author on his inauguration as extra-mural professor at the Technische Hogeschool Eindhoven. The subject matter is that of investigations of the atmosphere with the aid of radio waves. After recalling the historic work on the ionosphere done by Appleton and Barnett and by Breit and Tuve, the author mentions the recent work of Bowles, who, by radar soundings from the earth, has obtained data on the upper region of the F layer. These data confirm observations made by instruments on board artificial satellites, namely that the electron density above the middle of the F layer changes much more slowly with height than below it. Amongst the important discoveries made possible by the development of astronautics are the Van Allen zones of intense radiation at distances of more than 2000 km from the earth. Other subjects discussed are the transition from the atmosphere to the region of interplanetary gas, the existence of winds and tides in the ionosphere, and the use of radar for observing meteors.

MICROPHONY IN ELECTRON TUBES

by S. S. DAGPUNAR *), E. G. MEERBURG **) and A. STECKER ***).

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Microphony may be defined as the occurrence of an electrical interfering signal produced as a result of mechanical or acoustical vibrations of a circuit element, e.g. an amplifying tube. The effect is as old as the radio tube itself. At first it could be kept within bounds by mounting the tubes in resilient holders. At the levels of amplification common nowadays, however, this simple measure is far from sufficient. Theoretical and experimental investigations have shown what can be done in the design and construction of a tube to minimize microphonic effects. The article below, which embodies contributions from British, Dutch and German laboratories, gives some idea of these investigations and of the progress made in recent years in combatting microphony.

Introduction

Amongst the component parts of radio sets, amplifiers, etc., there are many that do not constitute a mechanically rigid assembly, but consist of parts capable of physical vibration at a frequency generally within the audio region. As the parts vibrate the distance between them alters, and this is accompanied by fluctuations in the electrical properties of the circuit element involved. Take, for example, a variable capacitor: if the plates vibrate with respect to one another, the result is a periodic variation in the capacitance. If the capacitor is part of the tuned circuit of an oscillator, the frequency of the generated voltage will also vary periodically, i.e. it will be subjected to frequency modulation, giving rise to interference in the output signal. This production of an interfering signal as a result of mechanically vibrating components is known as microphony.

Electron tubes are particularly subject to microphony, and in this article we shall be concerned solely with microphonic effects in electron tubes. Physical vibration of the electrode assembly not only causes variations in the capacitances between the electrodes but also fluctuations of the anode current and mutual inductance, and hence directly affects the gain of the tube.

There are many causes of vibration in an electron tube. Apart from incidental vibrations or shocks, there are those to which car radios, transceivers, radio equipment in aircraft, etc., are constantly subjected, there are the vibrations due to the motor in gramophones and tape recorders, the mechanical shocks caused by the operation of switches in various equipment, and above all the vibrations caused by the loudspeaker. Loudspeakers are often placed very close to amplifying tubes and can transmit vibrations to the latter both acoustically (via the air) and mechanically (through the cabinet, the chassis and the tube holders). This situation is particularly dangerous in that the loudspeaker itself reproduces the interfering microphony signal; if the gain is sufficiently high, this may give rise to acoustic feedback ("howling"), and if not, it may in any case produce troublesome reverberation. Microphony can also produce severe interference in television receivers. Loudspeaker vibrations here may be transmitted to amplifying tubes in the high frequency, intermediate frequency or video frequency part of the receiver, causing troublesome fluctuations in the brightness of the picture. Microphony in tubes in the deflection circuits may distort the picture as well as cause displacements in lines.

In recent years extensive investigations have been carried out in many laboratories both into the requirements to be met by tubes in modern equipment in order to minimize microphonic effects, and into the measures that can be adopted to make the tubes fulfil these requirements. This article will deal with the work done along these lines in various Philips laboratories and the results obtained [1]).

*) Mullard Radio Valve Co., Ltd., Mitcham, England.
**) Electron Tube Division, Philips, Eindhoven.
***) Development Laboratory of Valvo GmbH, Radioröhrenfabrik, Hamburg.

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Factors determining the strength of the microphony

An electron tube subjected to acoustical and/or mechanical vibrations undergoes a periodically alternating acceleration. It is the magnitude of this acceleration that primarily determines the strength of the microphony. To give an idea of the accelerations involved, it may be mentioned that measurements with vibration pick-ups in radio and television receivers have shown [2]) that a loudspeaker fed with a power of 50 mW gives rise to tube accelerations from 0.1g to 0.25g (g = acceleration of the force of gravity). A higher power evidently causes greater accelerations, the increase being proportional to the root of the power. In car radios the accelerations produced by engine vibrations are much greater than those caused by the loudspeaker. Of course, the type of car, the state of the engine and other conditions are important in this respect. Tests made on the instrument panels of numerous types of cars have shown that, under certain circumstances, accelerations up to 25g may occur.

Apart from the magnitude of the vibrations to which the tube as a whole is subjected, the extent to which the vibrations are transmitted from the base or wall of the tube to the electrodes also has an important bearing on the strength of the microphony. Further factors involved are the stiffness of the components and the rigidity of their mountings.

A further point to be taken into account in this connection is the function of the tube in the apparatus concerned, since this function determines the parameter whose fluctuations may prove most troublesome. For instance, where a tube is to be used in a low-frequency amplifier, changes in the capacitances between the electrodes will seldom be important, whereas variations in the anode current as a result of electrode vibrations may be very important indeed, since these variations, after amplification, are usually applied to the loudspeaker and made audible. Capacitance variations, on the other hand, can be very troublesome in the oscillator tube in a superheterodyne receiver, particularly if the receiver is tuned to a high frequency. In that case the circuit capacitance is small, and as a result the tube capacitances have a considerable effect on the frequency of the voltage generated by the oscillator. Periodic variation of these capacitances thus gives rise to frequency modulation which, in an FM receiver, is heard through the loudspeaker. This may also be the case in an AM receiver if the set is not exactly tuned to the received signal. Variations in the frequency of an IF signal then give rise to amplitude modulation which, after detection, again results in an interfering low-frequency voltage. Amplitude and frequency modulation may also be caused by capacitance variations in one or more of the radio frequency or intermediate frequency circuits of a receiver, giving rise to fluctuations in the magnitude and phase of the output voltages of the amplifier stages involved.

In cases where microphony causes fluctuations of mutual conductance, the effect can be troublesome if the tube is used in the radio frequency or intermediate frequency circuits of an AM receiver, since a periodically varying mutual conductance results in a variable gain, and thus modulates the RF or IF signal voltage in amplitude.

Microphony in a tube is more troublesome the more amplifier stages are connected behind the tube, in which case a correspondingly smaller variation in one of the parameters of the tube will be sufficient to produce an impermissibly large alternating current to the loudspeaker.

Inconsistent nature of microphony

Because of the numerous factors governing its strength, microphony in practice is an irregular, inconsistent phenomenon. A tube fulfilling a certain function in a particular apparatus may give no difficulties, whereas in another function or another apparatus it may exhibit excessive microphony. The location of the tube and the position in which it is mounted may also have considerable influence. Moreover, individual tubes of the same type may show marked disparities. In spite of the extremely narrow tolerances used in the manufacture of components, it is impossible to avoid slight constructional differences from tube to tube. This has no significant effect on the purely electrical properties of the tube, but it may give rise to considerable differences as far as microphony is concerned. Consequently, certain practical methods of testing can only be carried out on a statistical basis; whether a particular modification introduced in a tube will improve the tube's microphonic behaviour in practice can only be established by investigating a fairly large number of individual tubes.

The inconsistent nature of microphony is accentuated by the fact that the frequency spectrum of the vibrations to which the tubes are subjected in practice is extremely irregular in shape. The reason for this is that the chassis, the cabinet and other structural elements of electrical apparatus exhibit many different resonance frequencies for mechanical and acoustical vibrations, so that the whole assembly behaves as if it consisted of large numbers of

[2]) See the article by Hellmann under [1]).

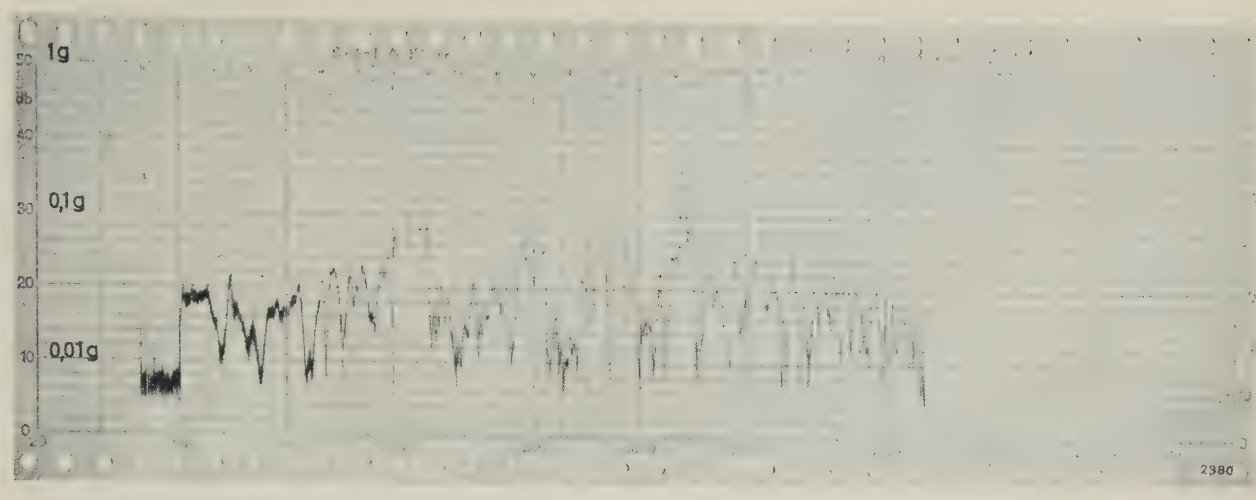


Fig. 1. Frequency spectrum of the acceleration to which a tube in a certain type of radio receiver is subjected when the loudspeaker is driven by a constant power of 50 mW at a varying frequency.

mutually coupled resonators. *Fig. 1* shows an example of a frequency spectrum of the acceleration undergone by a tube in a radio receiver when a constant electrical power of 50 mW is supplied to the loudspeaker at a variable frequency. A frequency spectrum of this kind is obtained by substituting for the tube a vibration pick-up, mounted in a container whose dimensions and weight correspond approximately to those of the tube.

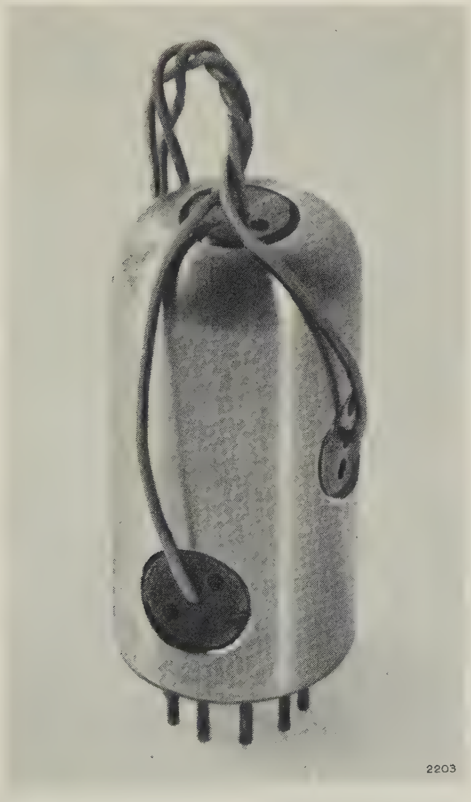


Fig. 2. Combination of three vibration pick-ups, used for measuring the vibrations to which tubes are subjected in electronic equipment. The whole assembly can be fitted in a tube holder in place of a tube.

Where three pick-ups are used, mounted in directions perpendicular to each other, one can also determine the direction in which the accelerations occur. Such a combination of three vibration pick-ups is shown in *fig. 2*. The whole assembly is roughly as heavy as an electron tube and can be inserted in one of the tube holders in the apparatus under test.

Methods of investigating microphony

There are various direct methods of investigating microphony that can easily be carried out without special equipment. For instance, the microphonic tendency of an audio amplifying tube can be ascertained by incorporating the tube in an amplifier circuit. The output voltage is applied via a

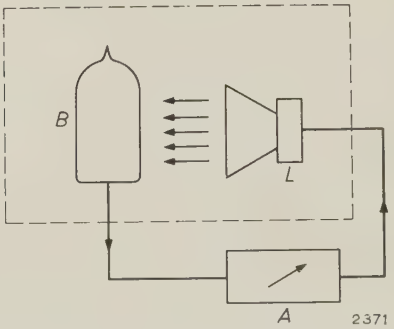


Fig. 3. Principle of a simple set-up for investigating microphony in an audio-frequency amplifying tube. *B* tube under test, *L* loudspeaker, *A* variable amplifier.

variable amplifier to a loudspeaker set up near the tube. This arrangement is shown schematically in *fig. 3*, where *B* is the tube under test, *L* the loudspeaker and *A* the variable amplifier. The gain of *A* is adjusted until it is just sufficient to cause acoustic

oscillation, after which the "sensitivity" of the combination of B and A at this setting is found. This is generally taken to mean the alternating voltage required on the control grid of B in order to produce an output of 50 mW from A. The gain setting of A so found is clearly too high when used with the tube B; it is thus possible to give a sensitivity of the combination that *is* permissible, to guide users of this type of tube.

Obviously, a specification of this kind is useful only in a circuit arrangement exactly corresponding to that with which the experiments were carried out. A small constructional change in the apparatus in which the tube is used can considerably alter the tendency to microphony. For this reason, and because of the above-mentioned spread between individual tubes of the same type, it is always necessary to allow a wide safety margin.

A radio-frequency tube can be tested in a similar way. The tube is incorporated in an RF amplifier stage and an unmodulated RF signal voltage is applied to the control grid (see *fig. 4*). A detector is

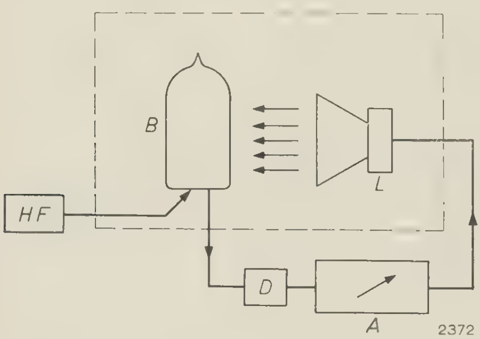


Fig. 4. Principle of a set-up for investigating microphony in a radio-frequency amplifying tube. B tube under test, L loudspeaker, A variable amplifier, D detector, HF signal generator.

connected to the output of this amplifier stage, which is again followed by a variable audio-frequency amplifier and a loudspeaker. Microphony now causes modulation of the RF voltage, and the detector delivers an audio signal which, via the AF amplifier and the loudspeaker, can produce acoustic oscillation.

The methods described can be used for comparing different types of tubes or individual tubes of the same type, and also for checking the results of modifications made in a tube to reduce microphony. They give no indication, however, as to which components in a tube cause the microphony, and are therefore no help as regards the introduction of the necessary improvements.

In this respect another method is helpful. Instead of making the set-up howl, the loudspeaker is connected to a separate signal generator and amplifier, and the output voltage of the tube is measured with the aid of an amplifier and a vacuum-tube voltmeter (*fig. 5*). This makes it possible to choose

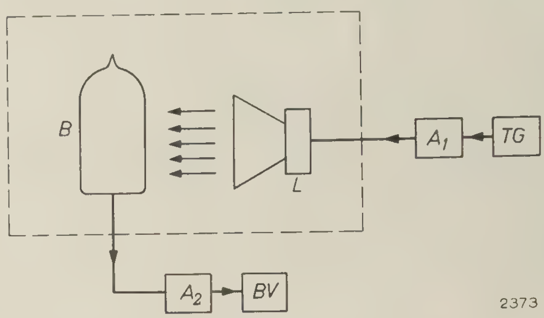


Fig. 5. Principle of a set-up for investigating microphony in electron tubes. The loudspeaker L is fed via the amplifier A_1 with a voltage from the signal generator TG. The signal voltage due to microphony in tube B is applied to a vacuum-tube voltmeter BV via the amplifier A_2.

and to vary the frequency of the vibrations to which the tube is subjected. The strength of the microphony is then found to vary quite irregularly with the frequency. This is partly due to the fact that the components of the electrode system have different resonance frequencies for mechanical vibrations, so that the tube behaves as if it consisted of a large number of mutually coupled resonators. A further factor, however, as mentioned above and illustrated in fig. 1, is that, even where the loudspeaker power is constant, the acceleration undergone by the tube shows a highly irregular spectrum. As a result, it is not easy to study the microphonic properties of electron tubes with a set-up as in fig. 5: there is always the possibility that the cause of strong microphony occurring at a particular frequency may lie outside the tube itself.

To arrive at results that are governed solely by the tube we must therefore set the tube in vibration directly and not via a loudspeaker, a cabinet and a chassis.

One method of achieving this is to subject the tube to an impact of given strength and to measure the resultant microphonic signal voltage. An apparatus designed for this purpose is shown in *fig. 6*. Even here, however, the results are not very satisfactory. A blow brings all components of the tube simultaneously into vibration, and only the total result can be measured from the signal voltage thereby generated. Consequently, this method too is really only suitable for comparing tubes one with the other, and not for tracing the causes of microphony.

A thorough study of the microphonic properties of tubes demands that the tubes be subjected to vibrations of constant acceleration and variable frequency. Only then is it possible to draw con-

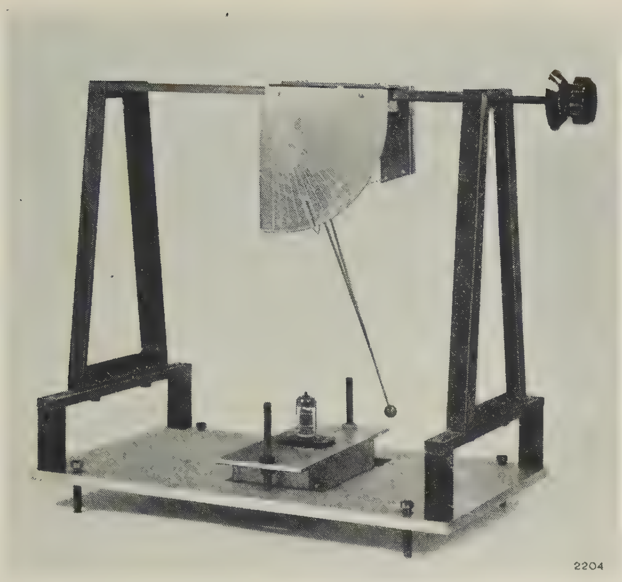


Fig. 6. Apparatus for studying the microphonic properties of electron tubes by subjecting the tube to a known impact.

clusions, or at least inferences, as to the cause of strong microphony at a particular frequency.

With this object in view, the constant acceleration has been achieved by testing the tubes in a specially designed vibrator. This method has for some time now been applied in several Philips laboratories to numerous types of tubes, and will now be discussed in some detail.

A vibrator for the study of microphony

Fig. 7 shows an axial cross-section through a vibrator designed for investigating microphonic effects in electron tubes. The construction of the vibrator closely resembles that of an electrodynamic loudspeaker. It consists primarily of a coil which can move in the air gap of a ring-shaped magnet. The coil is wound on an aluminium former, which is supported in sleeve bearings. The resonance frequency of the whole assembly is in the region of 30 kc/s, which is a great deal higher than the highest frequency of the range in which microphony tests are usually made (30 to 20 000 c/s). In this frequency range, then, where the alternating current in the coil is constant an alternating acceleration of almost constant peak value is obtained. (An alternating current of 100 mA was needed for a peak acceleration of 1g.) This can be quite easily checked by mounting a stationary metal plate a short distance from the upper surface of the coil and by measuring the variations occurring in the capacitance between this plate and the coil, this capacity being inversely proportional to the distance. For a constant charge, voltage variations appear across the capacitor thus formed, the magnitude of which is proportional to the deflection of the vibrator. These voltage variations can be amplified and measured. It follows from the theory of harmonic vibrations that, if the peak acceleration is to remain constant, the maximum deflection must be inversely proportional to the square of the frequency, i.e. with increasing frequency it must decrease by a factor of 4 per octave. With the vibrator described here this was indeed found to be the case in the required frequency range.

The way in which the tube under test is fixed to the vibrator calls for particular care. Strictly speaking, it should be perfectly rigid, otherwise the vibrations of the coil former will not be transmitted to the tube completely independent of the frequency. Now, some resilience in the mounting of the tube is unavoidable and consequently the tube resonates at the frequency of the mounting. To prevent

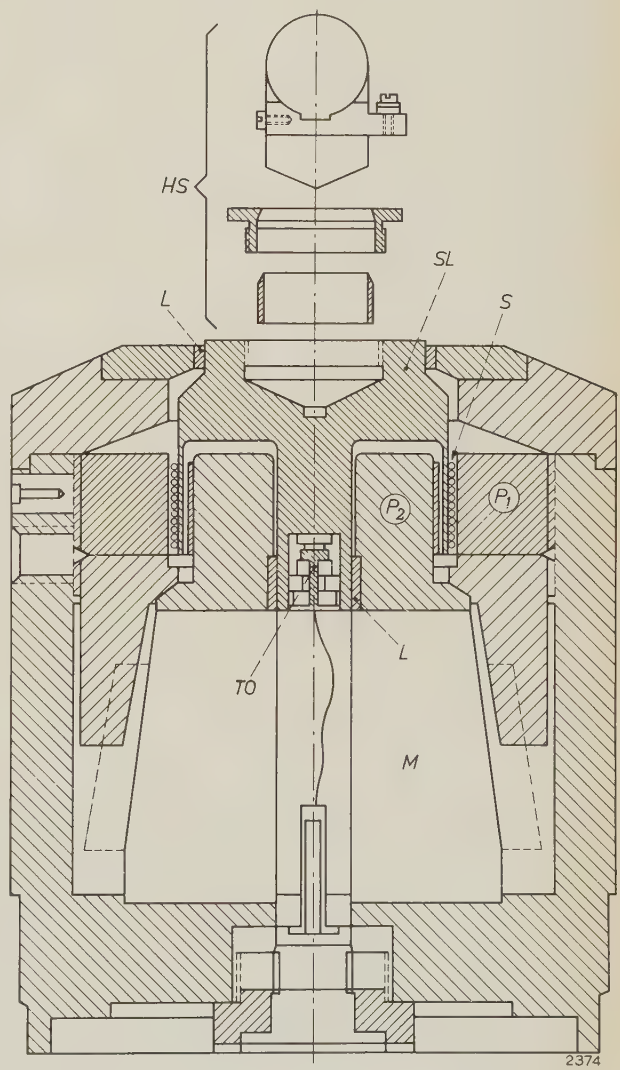
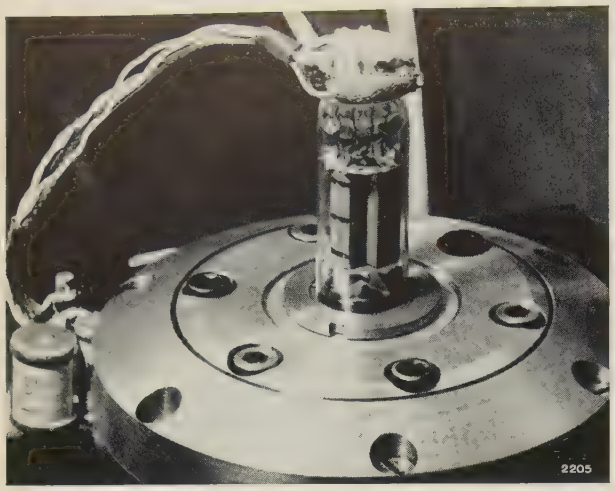
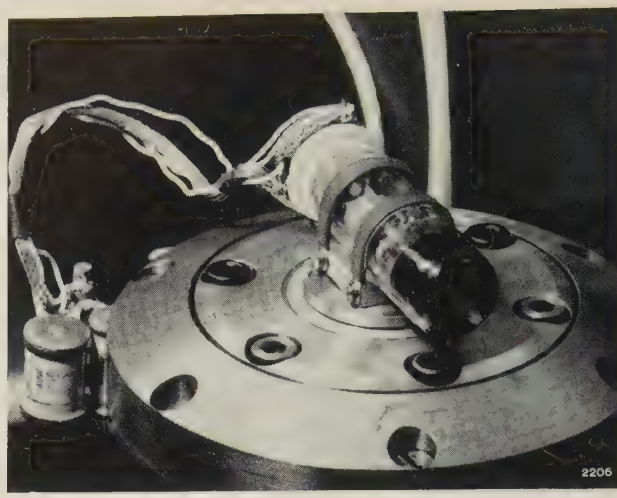


Fig. 7. Cross-section of a vibrator for studying microphonic effects in electron tubes. *S* coil, *SL* coil former, *L* sleeve bearings, *M* magnet, P_1 and P_2 pole pieces, *TO* vibration pick-up, *HS* adaptors for clamping the tube to the coil former.



a



b

Fig. 8. Upper part of vibrator fitted with a tube to be subjected to vibrations: *a*) along the axis; *b*) perpendicular to the axis.

this affecting the measurements, the vibrator and mountings must be so designed that the resonance frequency is well above the frequency range under investigation. Some components used for this purpose are shown in the upper part of fig. 7.

To enable a constant check to be kept on the vibrations, a vibration pick-up of the piezo-electric type is fitted (with a piezo element of barium titanate); this is denoted by *TO* in fig. 7. This device also indicates whether insufficiently rigid mounting of the tube is causing a spurious resonance.

Fig. 8 shows two photographs of the upper part of the vibrator, with a tube mounted in two positions, enabling it to be subjected to vibrations parallel or perpendicular to the axis.

Measurements with the vibrator

With a vibrator as described above a tube can be subjected to a known acceleration which, as opposed to the methods illustrated in figs. 3, 4 and 5, is independent of the incidental resonance frequencies of other parts of the apparatus. If strong microphony appears at a particular frequency, it is now clear that this frequency corresponds to the resonance frequency of one of the tube components. Detection of these frequencies is accomplished by connecting the tube by flexible wires to an amplifying circuit: the signal voltage produced in this circuit as a result of microphony is measured whilst the vibrator frequency is slowly varied. The measurements are facilitated by using a recorder. Examples of spectrograms obtained in this way are shown in figs. 21-24.

In these and similar measurements the vibration frequency should be varied slowly and very evenly, the mechanical vibrations of the various components being very little damped. Because of the weak damping, the various resonances occur only very near to the exact resonance frequency: many peaks in the spectrogram are so sharp that they might easily be missed.

Once it has been found that a strong microphonic effect occurs at a particular frequency, the next thing to do is to trace the component responsible for it. There are various ways of setting about this. One obvious method is to calculate the resonance frequencies of components whose very slight movements can be expected, on theoretical grounds, to have a considerable effect on the electrical characteristics of the tube. One can then ascertain whether one of these frequencies coincides with a peak in the spectrogram. If this is so, it is reasonable to assume that the component in question must be the cause of this peak. Further experiments are then needed to show whether this assumption is correct or not.

In practice, this method turns out to be most unsatisfactory. The main reason is that calculations of the resonance frequencies of components in an electrode system can seldom be more than rough approximations. Exact formulae can be derived only for simple configurations, and the application of such formulae to practical cases calls for approximations and corrections; also, it is generally not accurately known just how the various electrodes are clamped or supported, or whether there is any play between them.

We shall illustrate the above method and its shortcomings by taking a grid as an example. The conventional grid construction is shown in *fig. 9*. Two uprights (or "backbones") S_1 and S_2 are mounted in holes in the mica discs M_1 and M_2. The grid wires *D* are wound helically around the uprights. If we now regard S_1 and S_2 as freely vibrating rods, their resonance

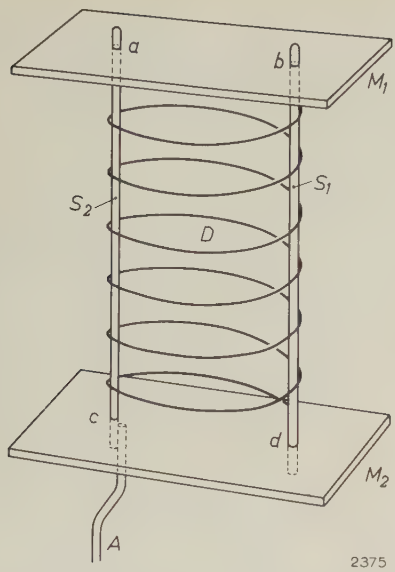


Fig. 9. Simplified construction of a grid. S_1 and S_2 uprights ("backbones"), D grid wires, M_1 and M_2 mica strips on which the assembly is mounted at the points a, b, c and d, A lead-in wire.

frequency f_r for mechanical vibrations can be calculated from the formula:

$$f_r = \frac{d}{4l^2} \sqrt{\frac{E}{\varrho}} K.$$

Here d is the diameter and l the length of the rod; E is the modulus of elasticity and ϱ the density of the material, and K is a constant which depends on the way in which the upright is held. The magnitude of this constant is:

$K = 0.56$ if the vibrating rod is clamped at one end and free at the other,

$K = 3.56$ if the rod is clamped at both ends,

$K = 2.45$ if the rod is clamped at one end and held such that it can pivot at the other,

$K = 1.56$ if the rod is held such that it can pivot at both ends.

Owing to the unavoidable spread in the dimensions of the grid uprights and of the holes in the mica supports, it is never certain whether the uprights at positions a, b, c and d should be regarded as clamped, pivoted or free. Extremely small differences in dimensions, which may have no perceptible effect on the electrical properties of the tube, may have a marked effect, in view of the differences in K, on the resonance frequency of the grid uprights. A further inaccuracy in the calculation is due to the presence of the grid wires D. Their effect can be allowed for as an increase in the mass of the grid uprights, but this is obviously a rough approximation. Finally, the fact that a connection wire A is attached to one of the uprights can also only be taken into account by very rough approximation.

For the grid wires two empirical formulae have been worked out [3]) which apply to wires bent in the form of an arc (*fig. 10a*) and in the form of a rectangle (fig. 10*b*). The formula for a grid wire as in fig. 10*a* is

$$f_r = \frac{0.217\, d}{2.78\, a^2 + 0.558\, R^2} \sqrt{\frac{E}{\varrho}},$$

and for a wire as in fig. 10*b*:

$$f_r = \frac{0.217\, d}{2.9\, a^2 + 0.325\, R^2} \sqrt{\frac{E}{\varrho}}.$$

These formulae hold good only when a and R are roughly the same ($R/a < 2$). Consequently, and also because the actual shape of the grid wires never exactly satisfies fig. 10*a* or *b*, the result here too can never be more than a very rough approximation.

Another source of uncertainty is the fact that many elements capable of mechanical vibration in an electrode system are coupled to one another, resulting in resonance frequencies that do not correspond to those of the elements individually.

Stroboscopic examination

The only way to point with certainty at one of the components of the tube as the source of strong microphony at a particular frequency is to observe directly that this component in fact resonates at that frequency, i.e. vibrates with a large amplitude. Since this "large" amplitude is not usually perceptible to the naked eye, it must be observed under a microscope. In order to make it possible to observe grids etc., it may further be necessary to make a number of tubes with special openings in the anode or in the screening.

As a rule the frequencies at which the investigations are carried out are too high for the eye to be

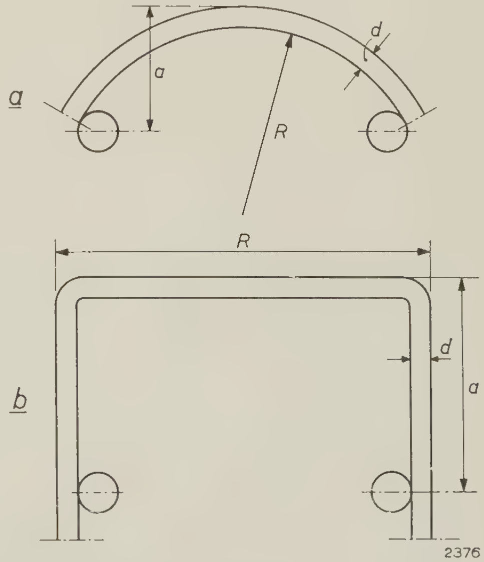


Fig. 10. *a*) Grid wire bent in the form of an arc, *b*) rectangularly bent grid wire.

able to follow the movement directly. The movements can be made visible, however, by illuminating the tube with a stroboscope. The vibrator and the stroboscope are then fed by two signal generators delivering alternating voltages whose frequencies differ by a few c/s. An arrangement designed for the purpose is shown schematically in

[3]) See P. M. Handley and P. Welch, Valve noise produced by electrode movement, Proc. Inst. Radio Engrs. **42**, 565-573, 1954.

fig. 11. When the tube is set in vibration, the parts in question can be seen under the microscope to vibrate at a frequency equal to the difference between the frequency of vibration and the illumination frequency. The fact that one of the parts

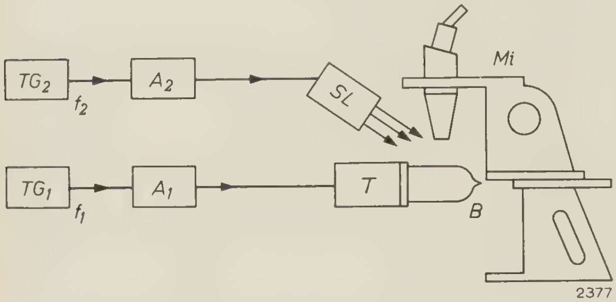


Fig. 11. Block diagram of an arrangement for stroboscopic investigation of microphony in electron tubes. TG_1 and TG_2 signal generators, A_1 and A_2 amplifiers, T vibrator, B tube under test, SL stroboscope lamp, Mi microscope.

is resonating at the applied frequency is manifested not only by the increase in amplitude but also by the phase relationship between the impressed force and the deflection.

When a vibrating system is driven by a force whose frequency is much lower than the resonance frequency of the system, the deflection is in phase with the force. If the frequency of the force is much higher than the resonance frequency, the deflection and the force are in antiphase. The transition from one of these states to the other takes place in a frequency range around the resonance frequency. The less the vibrations of the system are damped, the narrower is this frequency range. At the resonance frequency itself the phase shift between force and deflection is 90°.

To produce automatically a difference between the vibrator and the stroboscope of a few c/s at all frequencies, one might couple the tuning mechanisms of the two signal generators. It is very difficult, however, to make the coupling in such a way that the frequency difference remains sufficiently small over the whole frequency range of interest. If the difference is too great the eye can no longer follow the individual vibrations. When one of the components is then excited into resonance, the resonance will be scarcely perceptible.

An improvement in this respect is obtained if the stroboscope frequency is made exactly equal to the vibration frequency by connecting the vibrator and stroboscope to a common signal generator. Of course, the vibrating parts then appear to be stationary, the movement being frozen at all frequencies. When the frequency is slowly varied, however, and passes the resonance frequency of a component within the field of view of the microscope, the phase shift of 180°, mentioned above, can be seen to take place in the vibrations undergone by this component. As the frequency moves through a very small range, this part is then seen to make a single half-vibration and then stands still again. The concentrated attention required to observe this phenomenon is a serious drawback, however, to the application of this method in large-scale investigations. High demands are also made on the equipment; the frequency must be varied extremely slowly and continuously.

The stroboscopic method was not really a success until an apparatus had been designed with which it was possible, in the whole frequency range under investigation, to maintain a constant difference of 1 or 2 c/s between the vibration frequency and the frequency of the stroboscopic illumination. *Fig. 12* shows a block diagram of the equipment used for this purpose. As in fig. 11, the vibrator T is driven by a signal generator TG via an amplifier A_1. The output of the signal generator is again used to operate the stroboscope lamp, but only after first being applied to a frequency shifter FS which delivers an output voltage whose frequency is a constant amount higher or lower than the frequency of the applied voltage. The output voltage of the frequency shifter is used to control the pulse generator PG, which delivers short voltage pulses to the stroboscope lamp SL.

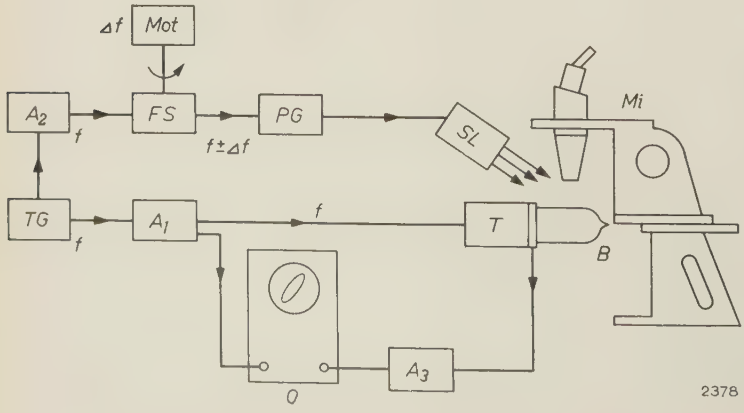


Fig. 12. Block diagram of equipment for stroboscopic investigation of microphony in electron tubes. By means of the frequency shifter FS a constant difference of 1 to 2 c/s is maintained between the vibration frequency and the frequency of the stroboscopic illumination. TG signal generator, A_1, A_2 and A_3 amplifiers, Mot motor, PG pulse generator, SL stroboscope lamp, Mi microscope, T vibrator, B tube under test, O oscilloscope.

The frequency shifter consists of a rotor and a stator. The stator is provided with a three-phase winding. This is supplied with a three-phase voltage derived from a special amplifier A_2, fed with the signal-generator voltage (frequency f). The rotating field thus produced induces an alternating voltage in the single-phase winding of the rotor. When the rotor is stationary, the frequency of the latter voltage is equal to f, but when the rotor revolves at a speed of Δf revolutions per second, the frequency of the e.m.f. induced in the rotor winding is an amount Δf higher or lower than f, depending on the sense of rotation. Provided the rotor turns at a constant speed, a constant frequency difference is then maintained between the applied voltage and the output voltage.

The tube under test B feeds an amplifier A_3, the output voltage of which is applied to one pair of plates of an oscilloscope O. To the other pair of plates a voltage is applied which is proportional to the current driving the vibrator. By observing at the same time the picture under the microscope and that on the oscilloscope screen it is now possible to ascertain with considerable certainty whether the vibrations of a particular component are responsible for the occurrence of strong microphony at a particular frequency. At that frequency the amplitude of the vibrations undergone by the component in question shows a maximum, and at the same time the alternating voltage produced by the microphony is seen on the oscillosope to reach a maximum value. The observer also sees the above-mentioned phase shift as the resonance frequency is passed. The phase shift also of course occurs between the current supplied to the vibrator and the voltage generated by microphony, and is thus displayed on the oscilloscope as a lissajous figure.

Owing to the extremely weak damping of the vibrations the effects referred to occur in such a very narrow frequency range that it is almost impossible for two or more components to resonate simultaneously, even when their resonance frequencies lie very close together.

Fig. 13 shows a photograph of a set-up as here described. With his left hand the observer varies the frequency of the signal generator, whilst with his right hand he directs the microscope and the stroboscope lamp on to the component to be examined. Over the edge of the ocular he can see the screen of the oscilloscope (right in figure).

The equipment described can also be used in another way. Instead of the amplified voltage output of a signal generator we can apply to the vibrator the amplified alternating voltage produced by microphony in the tube under test. In many cases this will give rise to oscillation at a frequency corresponding to the resonance frequency of one of the components. This component will then vibrate with a large amplitude, and it will not generally be difficult to ascertain by means of the microscope and stroboscopic illumination exactly which component this is. Of course, this method can only trace the component that makes the major contribution to the microphony, since oscillation occurs at the resonance frequency of that component. It is also possible, however, to find the cause of strong microphonic effects at other frequencies if we include in the feedback path a filter that passes signals only in a limited frequency band. In that case, oscillation can occur only at a frequency within that band, and the component responsible for it can be traced with the microscope.

In the method using an oscillating circuit it is even more important than in the other methods described that the resonance frequency of the vibrator-plus-tube assembly should lie above the range of frequencies under investigation. If that is not the case, the circuit might start to oscillate at this resonance frequency, and the search for the "guilty" component would then be fruitless.

Examples of microphony

It is unfortunately not possible in a photograph to give a good impression of the picture observed under the microscope when a component vibrates at its resonance frequency. Nevertheless, to give some idea of what is seen some photographs are shown that were obtained by double exposure at the extreme deflections of the vibrating component. With an arrangement as in figs. 12 and 13 it is a simple matter to freeze the observed picture of the vibrating component in any desired phase. All that is necessary is to stop the motor that drives the rotor in the frequency shifter. Obviously, the picture is then stationary too, and the required phase of the vibration can then be chosen by turning the rotor by hand.

Figs. 14 to 20 show various components of electron tubes and the picture seen under the microscope when the tube is made to vibrate at the resonance frequency of the respective component. The arrows indicate the direction of the vibrations.

Fig. 14 shows a getter which, being relatively large and supported on one side only, has a low resonance frequency, namely 300 c/s. It is evident that a component as large as this, though not part of the actual electrode system, must have a noticeable effect on the operation of the tube if set in vibration.

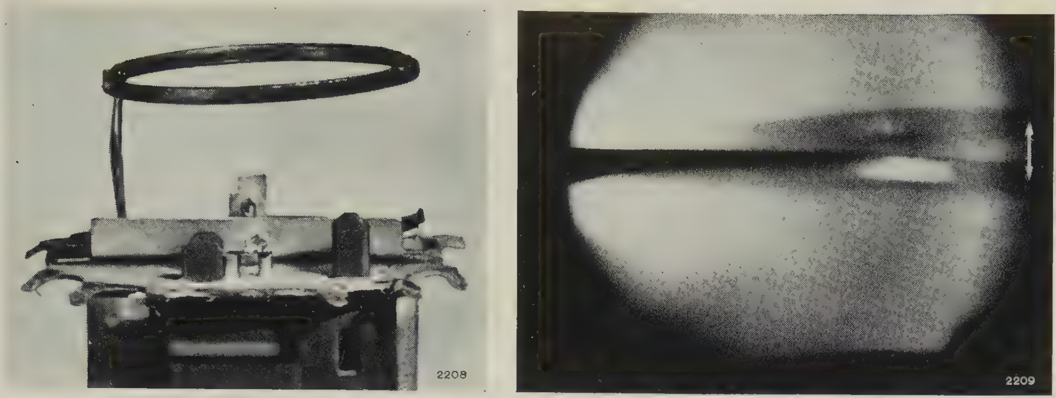
Fig. 15 shows the two filament leads of the tube, which have different resonance frequencies, viz. 570 and 600 c/s. The pictures observed under the

Fig. 13. Examining a tube for microphony. The arrow points to the tube under investigation.

microscope when the tube is made to vibrate at each of these frequencies appear in fig. 15*b* and *c*. It can be seen that, in each case, one of the two wires is virtually at rest whilst the other vibrates.

Fig. 16 shows the suppressor grid of a pentode made accessible to observation by an opening in the anode. Although the resonance frequencies of the turns of wire differ only slightly from one another, it can clearly be seen in fig. 16*b* that at the resonance frequency of one of them (approx. 2100 c/s) only that turn enters into vibration. This illustrates the fact that the mechanical vibrations are very little damped.

Grid-wire vibrations can cause impermissible microphony if they occur in the screen grid of a pentode in the RF or IF sections of a receiver. If the



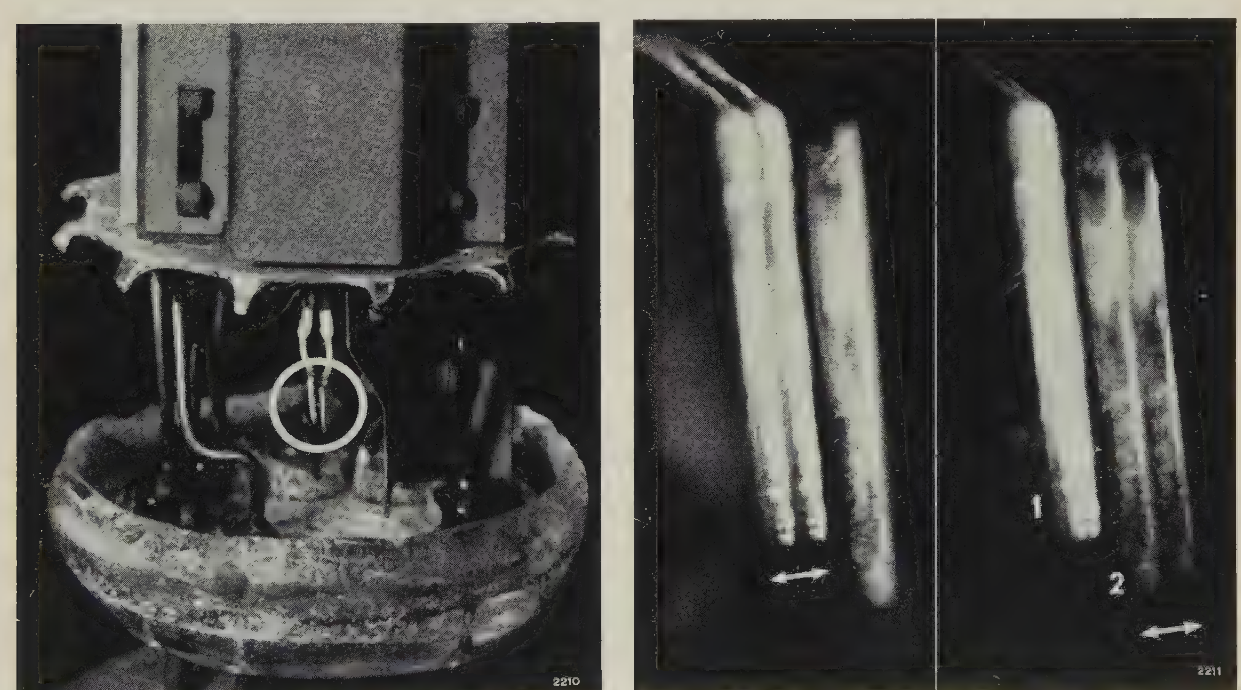
a *b*

Fig. 14. *a*) Getter of an electron tube.
b) Picture seen in the microscope when the tube is made to vibrate at the resonance frequency of the getter (300 c/s).

mutual conductance in the pentode has been reduced to a low value by the automatic gain control, the electron current passes through only a few turns of the screen grid. A slight movement of one of these turns then has a considerable effect on the anode current and on the mutual conductance. The effect is less pronounced if the tube operates with a higher mutual conductance. More nuisance is then experienced from vibrations in the grid uprights, since this causes lateral movement of the whole grid.

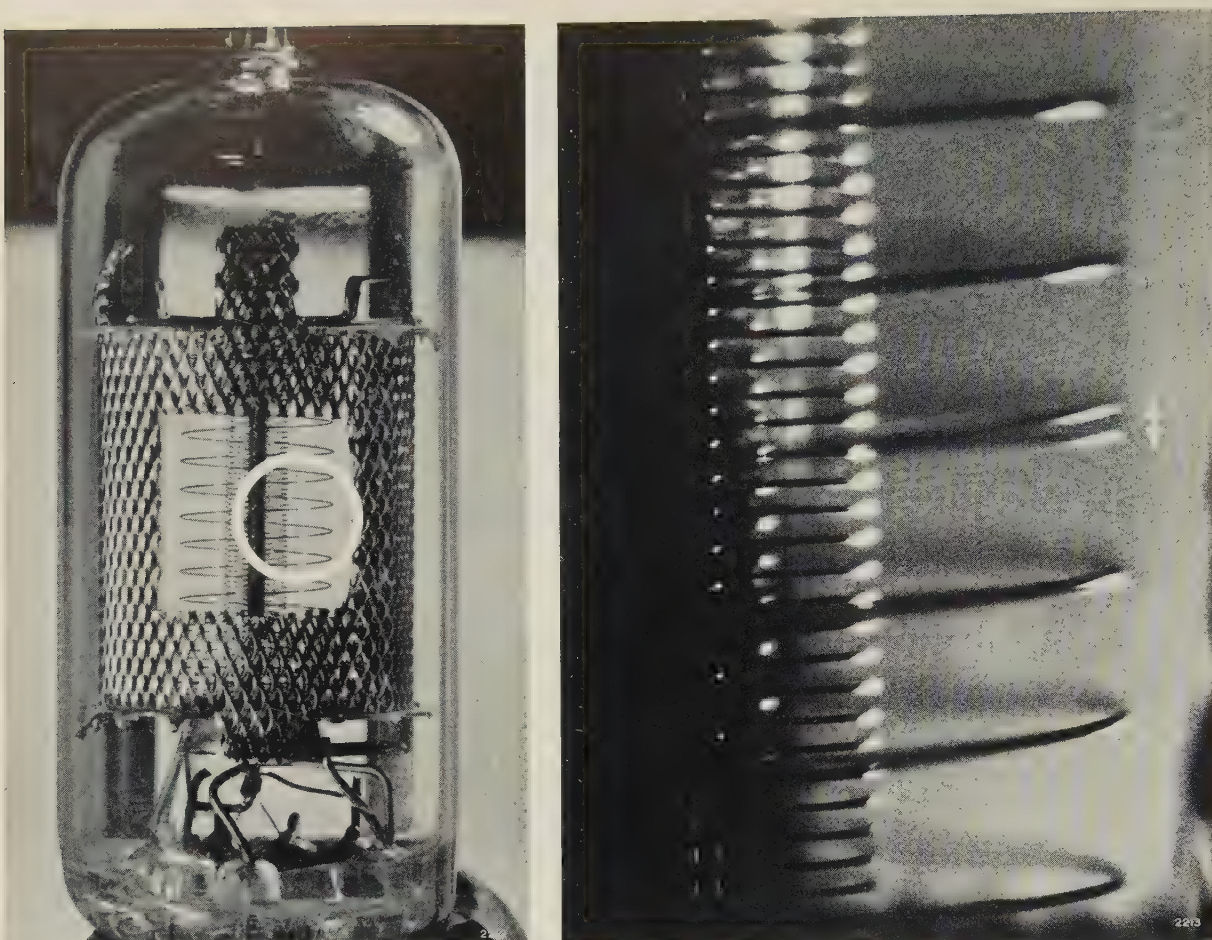
Fig. 17 shows a grid undergoing vibrations of this kind in the triode portion of a triode-hexode. Here, too, it was necessary to cut an opening into the anode. The resonance frequency of this grid was 1900 c/s.

In *fig. 18* the end of a cathode can be seen that exhibited some play in the upper mica support of the electrode system, and therefore vibrated at a very low frequency (600 c/s). Cathode vibrations are usually damped more than those of other components, owing to the influence of the filament with



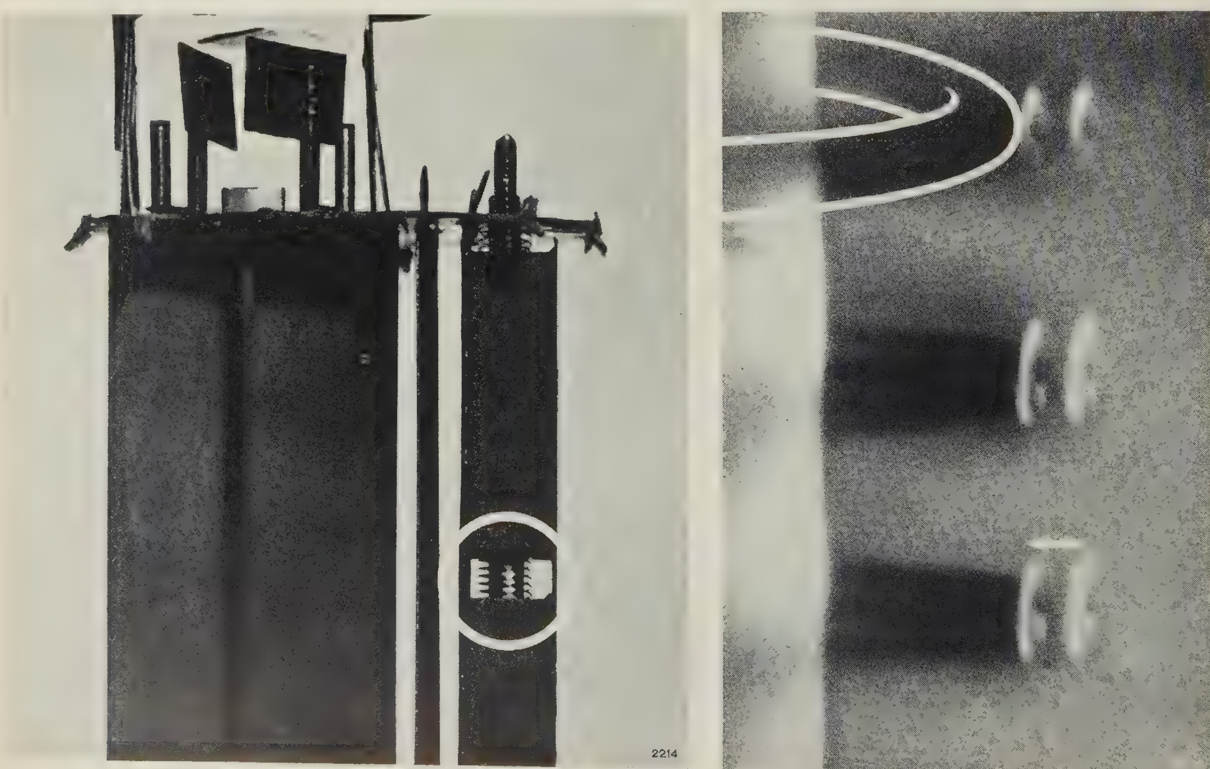
a *b* *c*

Fig. 15. *a*) Lower part of the electrode system of a vacuum tube. The circle marks the ends of the filament leads; *b*) and *c*) show the pictures of these leads seen under the microscope when the tube is successively made to vibrate at the resonance frequency of each lead (570 and 600 c/s).



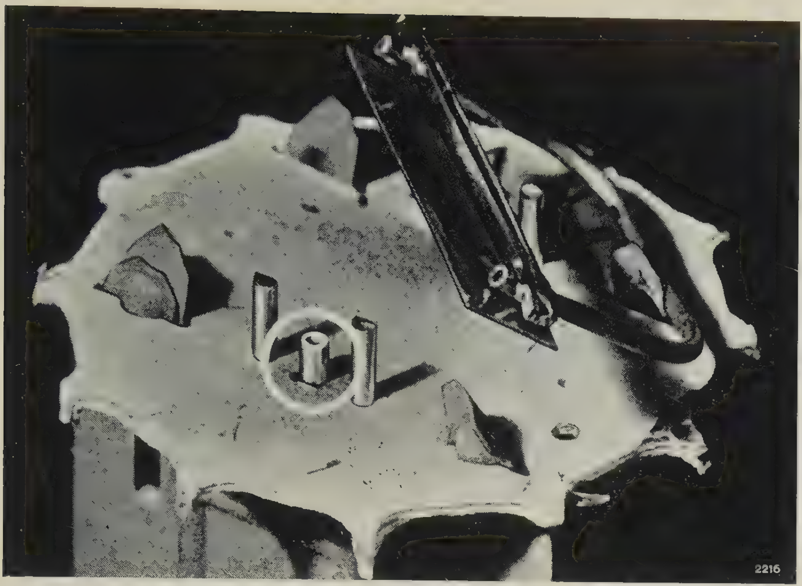
a *b*

Fig. 16. *a*) Suppressor grid of a pentode, visible through an opening cut into the anode. The circle marks the part seen under the microscope, (*b*), when the pentode is made to vibrate at the resonance frequency of one of the grid wires (2100 c/s).

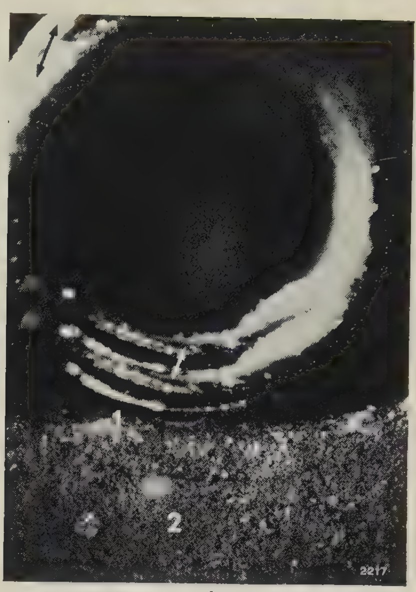


a *b*

Fig. 17. *a*) Electrode system of a triode-hexode. The circle marks the grid of the triode portion, visible through a hole cut into the anode. *b*) Picture of the grid vibrating at its resonance frequency of 1900 c/s.

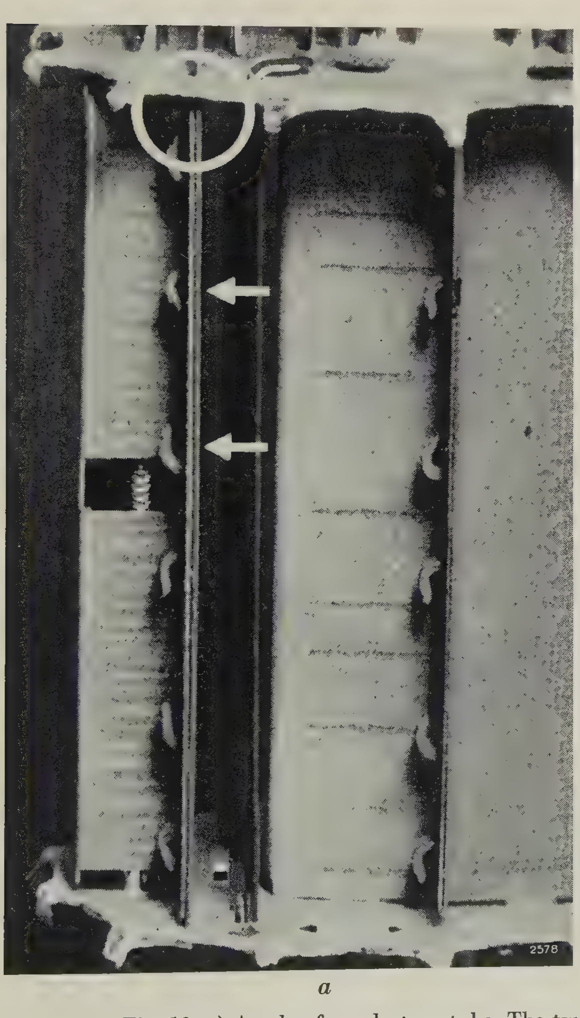


a

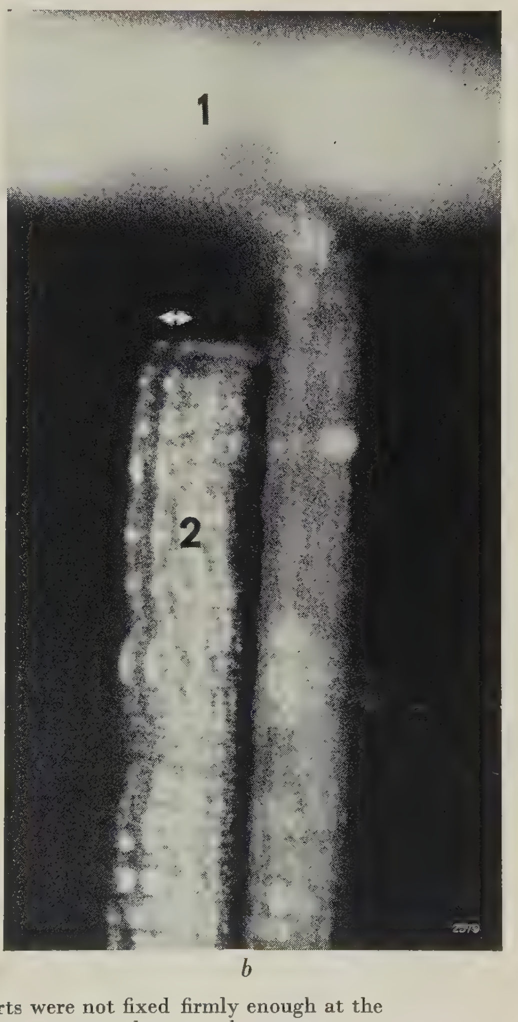


b

Fig. 18. *a*) Top view of the electrode system of a tube. The circle marks the end of the cathode, which showed some play in its hole in the mica disc.
b) Picture seen under the microscope when the tube was made to vibrate at the resonance frequency of the cathode (600 c/s).



a



b

Fig. 19. *a*) Anode of an electron tube. The two parts were not fixed firmly enough at the positions indicated by the arrows, thus allowing free movement between them.
b) Picture seen under the microscope of the circled area when the tube was set in vibration at a frequency of 1300 c/s.

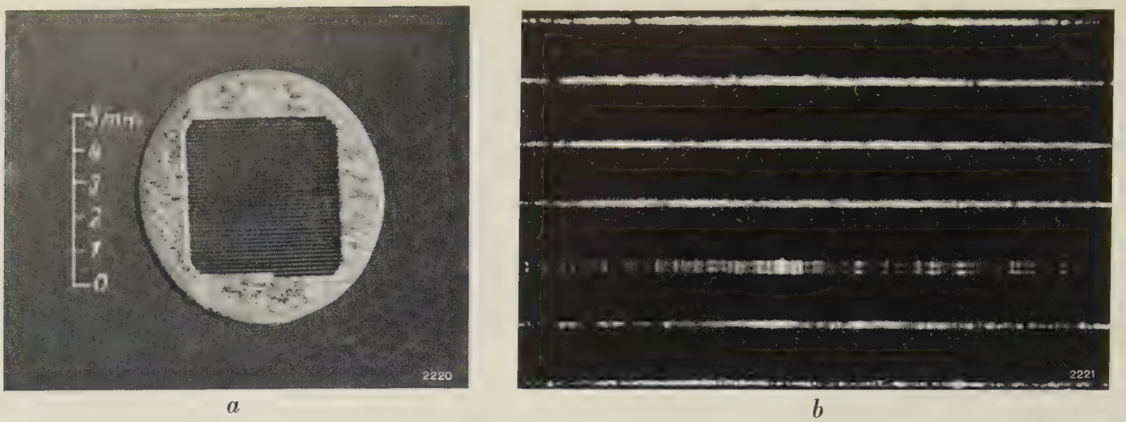


Fig. 20. *a*) Frame grid of a tube for very high frequencies.
b) Picture under the microscope when the grid was made to vibrate at the resonance frequency of one of the wires (37 000 c/s).

its insulation and to the emissive coating of the cathode.

Vibrations of one of the structural elements of an anode at a frequency of 1300 c/s can be seen in *fig. 19*. The reason for this vibration was that the parts of the anode at the position denoted by the arrows had not been properly fastened.

The fact that this method of investigation can also be used at higher frequencies than those mentioned above is illustrated in *fig. 20*, which shows

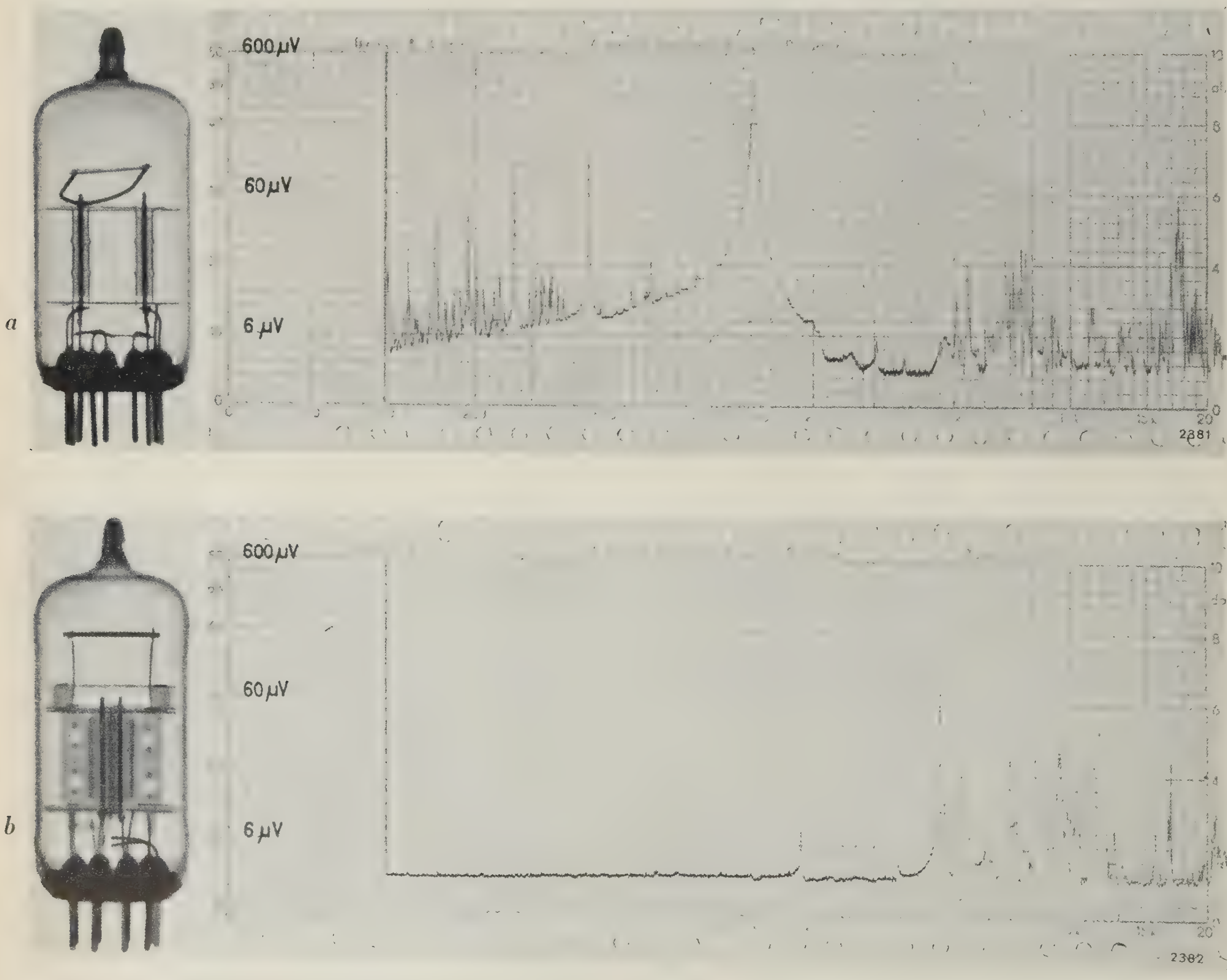


Fig. 21. Effect of getter construction on the microphony of an electron tube. The two constructions compared are shown on the left. The construction under *b* results in a considerable reduction of microphony.

the vibrations of one of the wires of a frame grid [4]). The frequency was 37 000 c/s. It need hardly be said that this imposes very high demands on the vibrator and on the rest of the circuit; the stroboscope lamp, for example, had to provide extremely short light pulses to produce a sufficiently sharp picture.

The reduction of microphony

Once it has been established that a particular component makes a substantial contribution to the microphony of an electron tube, it is of course important to ascertain whether a structural modification designed to reduce the microphony really has the desired effect. This can best be checked by recording a spectrogram of the signal voltage due to microphony as a function of the vibration frequency. We shall illustrate this with some examples of improvements introduced. Figs. 21 to 24 show a number of spectrograms recorded whilst the electrode systems of the tubes under investigation were subjected to lateral vibrations at a constant peak acceleration of $\frac{1}{3}$ m/sec^2. The figures indicate the rms value of the alternating grid voltage producing the same interfering signal as caused by the microphony.

Fig. 21 illustrates the result of modifying the support of a getter. The upper recording was made on a tube where the getter was fixed to a bracket which was welded to the anode at one point. This getter was found to be responsible for the strong microphony that occurred at a frequency of 1300 c/s. When the getter was secured at two places in the mica support, and thus no longer connected to one of the electrodes, a considerable improvement was obtained, as appears from the lower spectrogram. At frequencies below 1850 c/s the tube is now free from microphony.

Fig. 22 shows the improvement achieved when a single mounting lug on the anode was replaced by a

[4]) The construction of a frame grid is described by G. Diemer, K. Rodenhuis and J. G. van Wijngaarden, The EC 57, a disc-seal microwave triode with L cathode, Philips tech. Rev. **18**, 317-324, 1956/57.

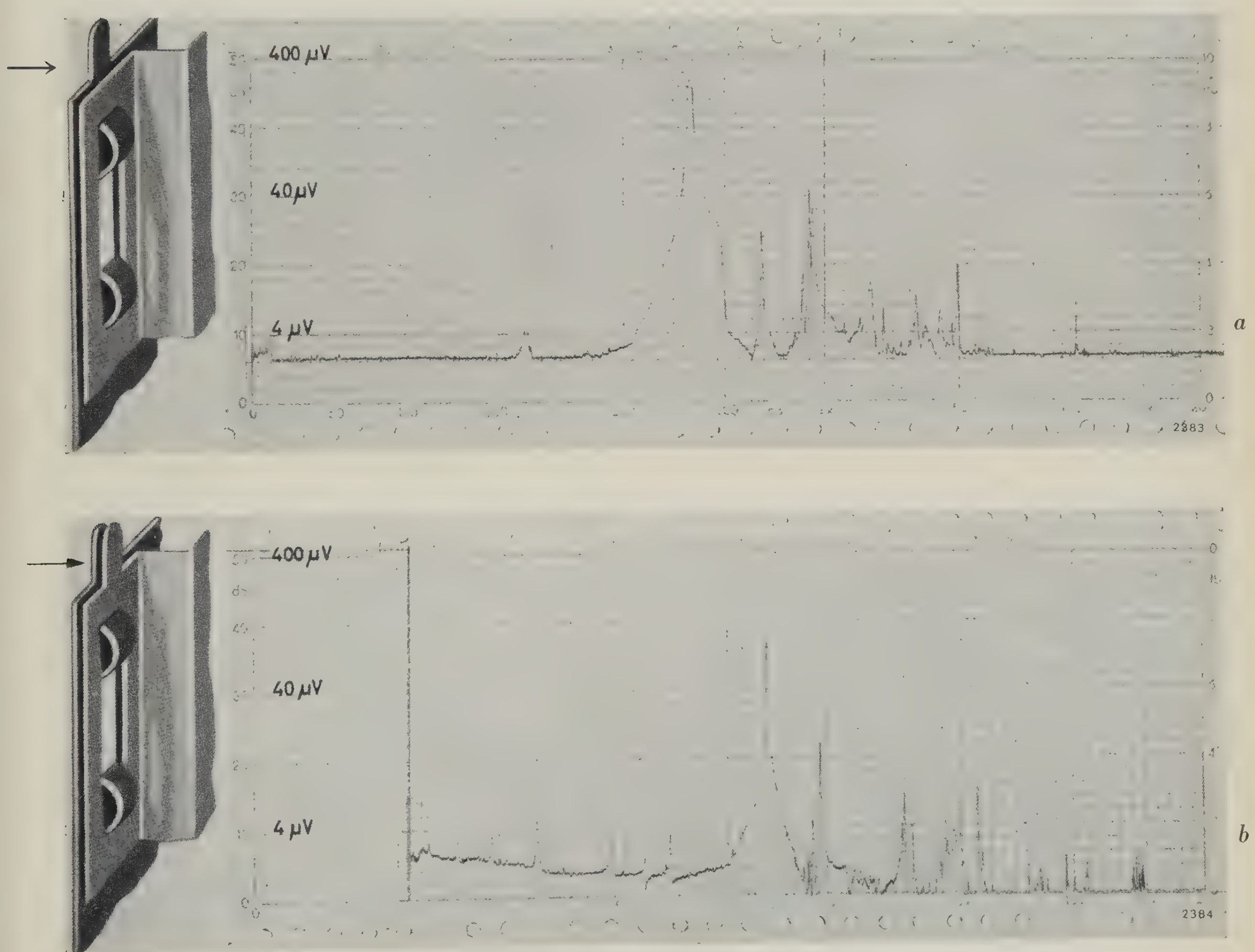
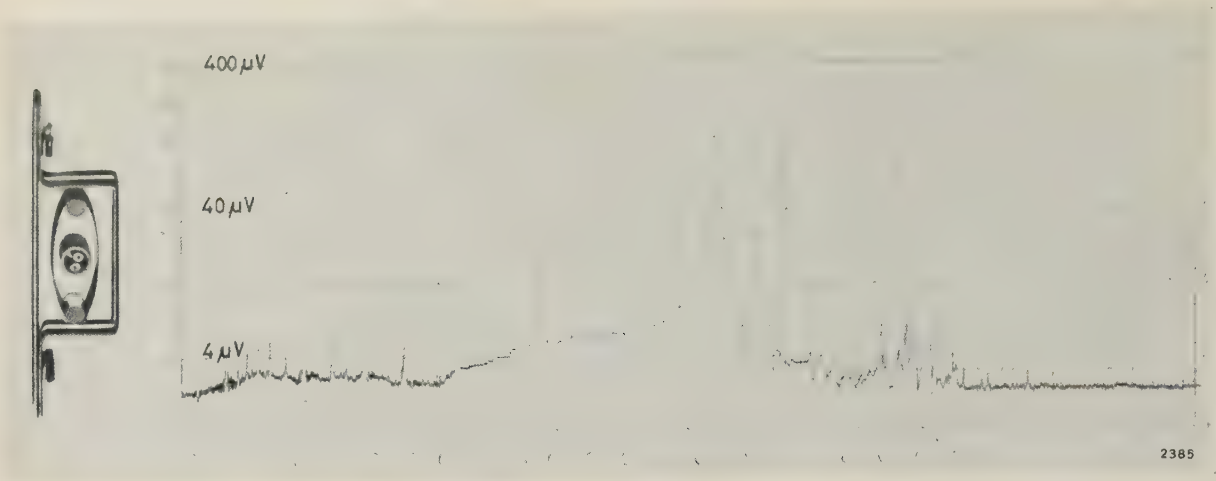


Fig. 22. Effect of anode fastening on the microphony of a tube. The method of fastening with a single lug (*a*) is inferior to that with a double lug (*b*).

a



b

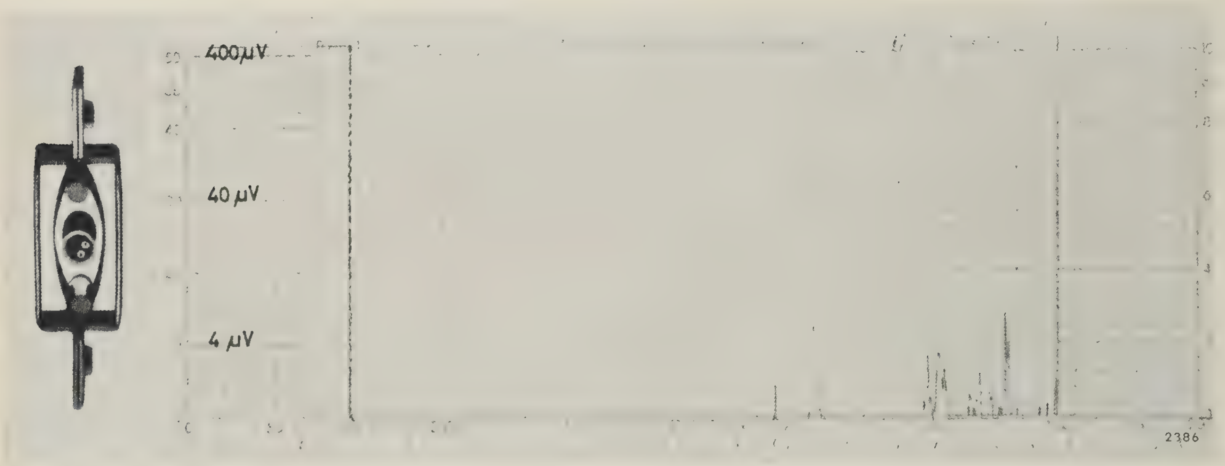


Fig. 23. The effect of anode design on microphony. The construction shown in (*a*) is greatly inferior to that in (*b*).

double lug, thereby eliminating the original play in the mica. In the construction shown in the upper figure, both parts of the anode were capable of relative vibration; as can be seen in the lower figure, the vibration is much less pronounced with the new construction. The high peak at about 780 c/s in the upper spectrogram is no longer to be seen in the lower recording.

The improvement obtained in another case, by modifying the construction of the anode, appears from *fig. 23*. An anode consisting of two rectangular sections, as in *b*, is far more rigid than an anode one of whose parts is flat, as in *a*. The marked improvement from the point of view of microphony is clearly to be seen in the spectrograms.

If the various components that give rise to microphony can be systematically traced and improved, the microphony can be almost entirely eliminated, as illustrated in *fig. 24*. The upper spectrogram relates to a tube which exhibited very troublesome microphony at various frequencies. The lower spectrogram, recorded after the necessary structural improvements had been made, shows that the tube is now virtually free from microphony.

It is not always possible in the series production of tubes to introduce all the improvements that would be desirable with an eye to microphony. Other considerations of quite a different nature may often be involved, such as the effect of these improvements on the electrical properties of the tube, on the cost price or on the production tools. However, if the causes of the microphony are sufficiently known — and they can nearly always be traced by the methods described above — a compromise can generally be found that satisfies these other requirements as well.

Noise method of investigating microphony

For tracing the causes of microphony the foregoing method yields good results. In certain cases, however, a simpler and less time-consuming method may be sufficient. This may be the case when the purpose is not to investigate the causes of

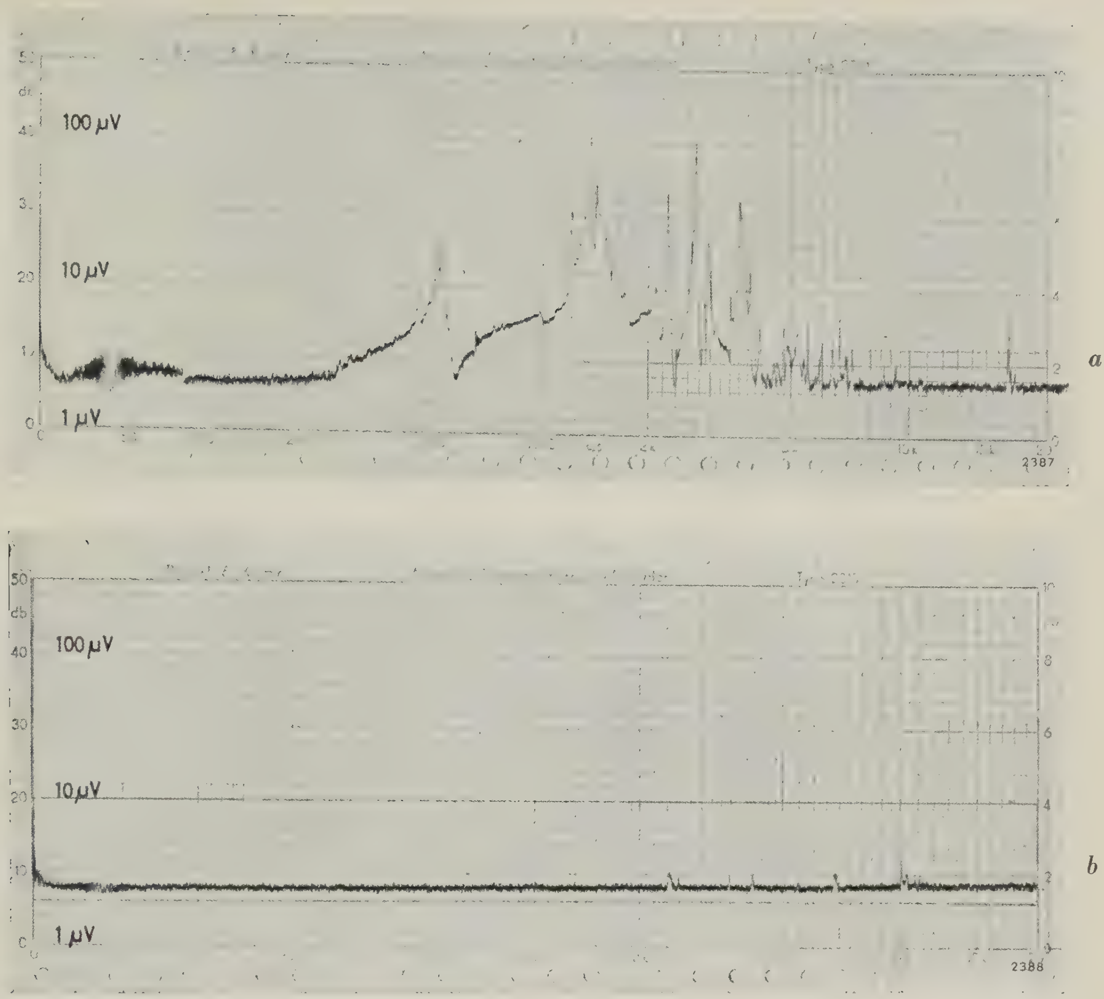


Fig. 24. Spectrograms of microphony in a tube, *a*) before and *b*) after certain structural modifications to reduce microphony.

microphony but simply to compare one tube with another in order, for example, to obtain statistical data on the effect of certain structural modifications. In such cases it is often enough to record a spectrogram. Using the method described earlier, viz. subjecting the tubes to sinusoidal vibrations with a variable frequency, several minutes will always be required to obtain a serviceable spectrogram. The frequency must not be varied too quickly because, as explained above, the mechanical vibrations of tube components are very little damped, and it is therefore likely that some peaks in the spectrogram will be missed if the test is done too quickly.

To conclude this account we shall briefly describe a method designed to produce a quicker result. The vibrator — and the tube under test — is excited not by a sinusoidal alternating current of variable frequency but by a current containing components with all frequencies at the same time, i.e. a current delivered by a noise source. In that case all components that have resonance frequencies in the frequency range under investigation will be excited into resonance simultaneously. If the tube is incorporated in an amplifier circuit, microphony gives rise to a signal composed of numerous alternating-voltage components. Measurement of the rms value of this signal gives in itself an idea of the extent to which the tube in question is "microphonic", but a better insight is obtained if the signal components are measured with a selective voltmeter which gives a reading in only a narrow frequency band. By shifting this small band over the whole investigated frequency range we can again obtain a spectrogram. This can be done in such a way as to display the spectrogram directly on an oscilloscope screen.

Fig. 25 shows a spectrogram produced in this way. Reproducible graphs can be obtained with the selective voltmeter

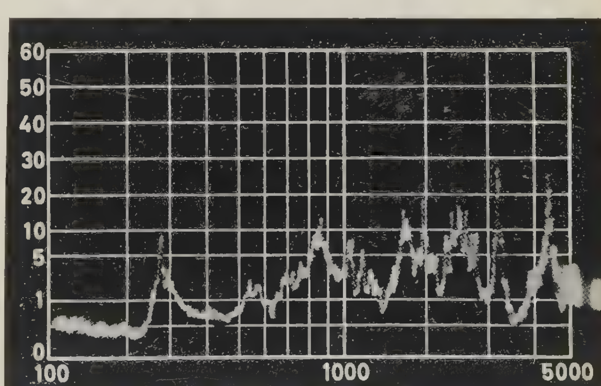


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Fig. 25. Oscillogram obtained using the noise method of investigating microphony.

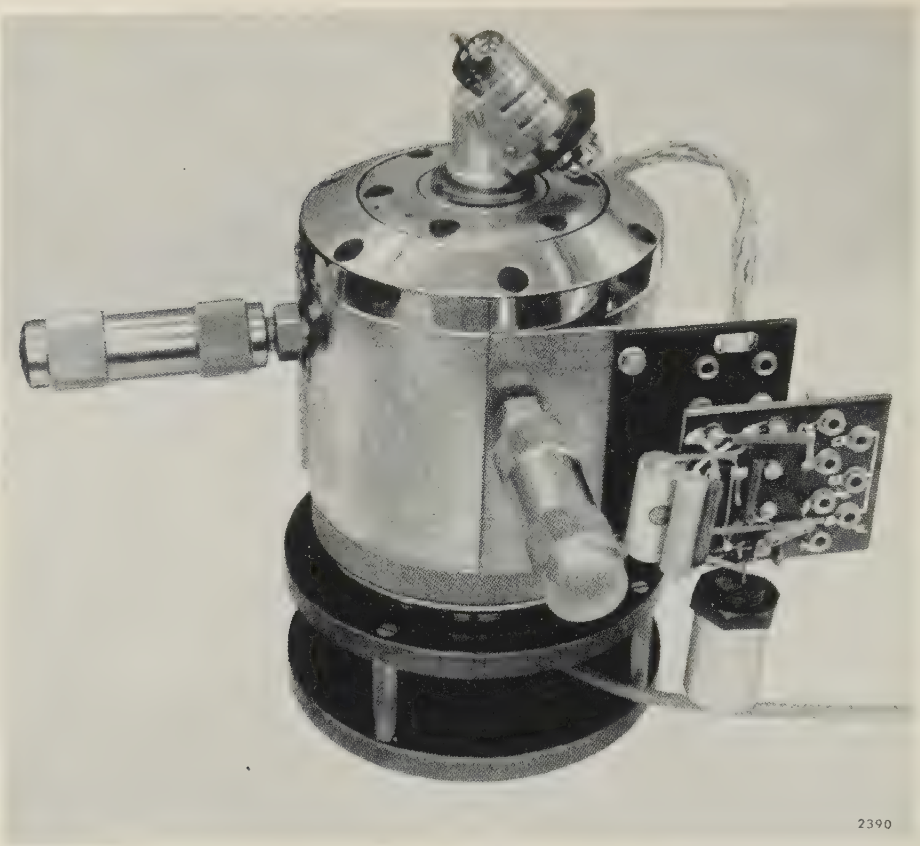

Fig. 26. Vibrator used for microphony investigations by the noise method. The tube under investigation is here mounted obliquely on the vibrator.

sweeping the whole frequency range in about 15 sec. Using an oscilloscope tube with a long-afterglow screen, the whole spectrum can be seen as a single display.

A vibrator used for investigating microphony by the noise method is shown in *fig. 26*. The tube is mounted obliquely in order to obtain a general picture of its microphonic properties, the tube thereby vibrating simultaneously in the lengthwise and lateral directions.

A drawback of the noise method is that the height of the peaks in the spectrum depends on their width. This is because the vertical deflection of the oscilloscope is proportional to the value of the microphony signal, averaged over the whole of the narrow frequency band passed by the selective amplifier. Consequently, a peak narrower than the bandwidth passed by the amplifier will appear to be shorter than a broader but otherwise equally high peak. The picture on the oscilloscope is therefore not an exact representation of the spectrum, and this must be taken into account when evaluating it.

Partly for this reason the noise method has not proved a great success. If one is prepared to accept this error, the results can be obtained just as quickly by the method using sinusoidal vibrations. When the whole frequency range is rapidly scanned, say in 15 seconds, here too the high peaks in the spectrum will not be reproduced in their true relationship. Even so, the resultant spectrogram is still better than that obtained by the noise method. Because of this, and the fact that the equipment for the noise method of investigating microphony is much more complicated, the system using sinusoidal vibrations has been given preference in our laboratories.

Summary. Various methods are described for investigating microphonic effects in electron tubes. Some direct methods requiring no special circuit arrangement can serve for comparing one tube with another, but they give no information on the cause of the microphony. For the latter purpose a vibrator has been designed by means of which a tube can be subjected to a vibration of constant peak acceleration and variable frequency. With the aid of a microscope and a stroboscope the components responsible for the microphony can then be traced by directly observing their vibration. Some results achieved are illustrated by spectrograms. Finally, a method using a noise generator is described, where the spectrogram is displayed on the screen of an oscilloscope.

THE HEATING OF FOOD IN A MICROWAVE COOKER

by W. SCHMIDT *).

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Growing interest is being taken in a novel method of cooking food, i.e. by dielectric heating in a short-wave electromagnetic radiation field. For cooking raw food, heating pre-cooked meals and thawing frozen foods the method is very quick and hygienic. Suitable sources of power for this purpose are now available in the form of two types of magnetrons capable of continuous outputs of 2 kW and 5 kW. "Microwave cookers" have definite advantages in hotels and restaurants, where large numbers of meals have to be served in a short time, but it may well be that they will eventually also find their way into the home kitchen.

In recent decades the heating of materials by high-frequency power has been applied on an ever-increasing scale in many branches of industry [1]). In the case of dielectric heating a limit is set to the delivered power by the electric breakdown strengths of the materials to be heated, which cannot withstand arbitrarily high voltages. The only way to increase the absorbed power is then to raise the frequency, hence the trend towards ever higher frequencies in dielectric heating.

In this respect the recent development of continuous-wave (CW) magnetrons giving an output of 2 and 5 kW represented an important advance [2]). These magnetrons operate at frequencies in the region of 2450 Mc/s, i.e. in the microwave range, and are particularly suitable for the dielectric heating of non-conducting materials. Besides their possible applications in industry, e.g. for drying wood and textile products, or for welding plastics, they have a promising application in the heating of foodstuffs, i.e. for preparing meals in a "microwave cooker". In this article we shall examine some of the problems involved in the construction of such a cooker using a 2 kW CW magnetron.

In the conventional methods of cookery (boiling, frying, roasting, baking, grilling) the heat is supplied by *convection* and *conduction* in water or fat, by *direct contact* with the heated pan or by *thermal radiation*. The heat in all these cases can only penetrate inside the food by conduction. The temperature gradient which this requires may not be too steep, as otherwise the surface of the food will suffer. The heating process therefore takes much longer than by the dielectric method, where the thermal conduction of the food is unimportant. In "microwave cookery" the food, with no water or fat added, is placed in a glass or earthenware dish, or even on paper or cardboard, and is heated through and through in a quarter or eighth of the normal time, without drying-out the surface of the food or scorching the paper. Pre-cooked or frozen foods can readily be warmed up again, the vitamins and the natural flavour, colour and other properties of the food being retained to a very high degree. There are various tricks by which the brown crust to which we are accustomed in conventional cookery can also be produced by microwave radiation; usually, however, a normal grill will be fitted to the oven for this purpose.

The use of a microwave cooker offers especial advantages for hotels and restaurants; the preparation of meals is very much quicker, and dishes can also be pre-cooked and warmed up when the time comes to serve them. This can be a great help in rush hours and where kitchen staff is short. In hospital kitchens experience has already proved that microwave cookers make it possible to provide a much more varied menu for patients on low-fat diets. Finally, a microwave cooker can also be a valuable asset in the home; a housewife who goes out to work will save a great deal of time preparing meals in this way, particularly if more pre-cooked meals in frozen form are made available by the foodstuffs industry.

In the following we shall first consider the physical principles underlying the method of dielectric heating in a microwave radiation field. After discussing the 2 kW CW magnetron marketed by Philips, we shall then examine the problems involved in the design of the oven proper, i.e. the space in which

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*) Development Laboratory of Valvo GmbH, Radioröhrenfabrik Hamburg.

1) See e.g. the articles Heating by high-frequency fields, I. Induction heating, by E. C. Witsenburg, and II. Capacitive heating, by M. Stel and E. C. Witsenburg, Philips tech. Rev. **11**, 165-175 and 232-240, 1949/50.

2) W. Schmidt, Das Dauerstrichmagnetron Valvo 7091, Elektron. Rdsch. **12**, 309-314, 1958; or, Continuous-wave magnetrons types 7091 and 7292, Electron. Appl. **20**, 13-23, 1959/60 (No. 1).

the food is heated. Finally, an experimental model is discussed by way of illustrating the actual construction of a microwave cooker.

Principles of dielectric heating in a microwave radiation field

At the frequencies commonly used for RF heating, the high-frequency power is fed into a coil or a capacitor. Conducting materials are heated in the magnetic field of a coil by the induction of eddy currents; non-conducting materials are placed in the alternating electric field of a capacitor, where the dielectric losses produce the desired heating. In the microwave range, i.e. at frequencies above 1000 Mc/s, the substance to be heated is placed in a resonant cavity, in which the electric and magnetic fields are so interwoven as to be practically indistinguishable. The "oven" of a microwave cooker accordingly consists of an appropriately dimensioned space bounded by metal walls. The microwave energy is conducted to the oven by waveguides. Multiple reflections from the walls fill the oven space with a radiation field, thus providing all-round irradiation of the food introduced. The method is suitable only for the dielectric heating of non-metallic objects, since the electromagnetic waves would be almost entirely reflected by good conductors.

If either pure dielectric or pure induction heating by microwaves is required this would be possible only in a small rectangular cavity whose ends run out into circular cylindrical spaces and whose length does not exceed $\lambda/4$. In the rectangular middle-section there will then be an alternating electric field between two walls which, at the frequency of 2450 Mc/s ($\lambda/4 = 31$ mm) are only 5 mm apart; in the cylindrical extensions there will be an alternating magnetic field of 10 mm diameter. Only very small objects could therefore be heated in these spaces, so that pure dielectric or pure induction heating at these frequencies has little practical significance.

Where an alternating electric field of amplitude E prevails in a medium, the heat P_W generated in unit volume and unit time is given by [3]):

$$P_W \propto E^2 f \varepsilon_r \tan\delta, \quad \ldots\ldots \quad (1)$$

where f is the frequency, ε_r the relative dielectric constant and δ the loss angle. This expression reveals the advantage of using microwave frequencies: even for small values of E a considerable heating effect is obtained because of the high value of f. Whereas at low frequencies the heat generation is limited by the breakdown strength of the material, in the microwave range the limit is set by the maximum power which the generator is capable of delivering.

When an electromagnetic wave is propagated through a (non-magnetic) medium, it is attenuated as a result of the heat generation: the energy density of the wave decreases in the direction of propagation. For a vertically incident plane wave the "penetration depth" z_i, which is conventionally defined as the distance at which the energy density has dropped to $1/e \approx 37\%$, is given by [3]):

$$z_i \propto \frac{1}{f\sqrt{\varepsilon_r}\tan\delta}. \quad \ldots\ldots \quad (2)$$

Table I gives the values of z_i calculated from measurements of ε_r and $\tan\delta$ on various foodstuffs. It can be seen that this penetration depth in some substances is rather small. Where fairly large volumes are involved there is consequently a danger that the substance will not be properly heated through. Equation (2) shows that the higher the frequency the less is the effective penetration of the heat. (In grilling this is, of course, turned to good advantage. Here, too, an electromagnetic radiation field is used — though of much higher frequency, i.e. in the infra-red — and this radiation is almost entirely absorbed in the surface layer, thus producing the familiar brown crust.) The limitation is not so serious as it seems, for in a resonant cavity the energy penetrates the substance from all sides. Moreover, experience has demonstrated that the results achieved in the cooking and thawing of

Table I. Values of ε_r and $\tan\delta$ for various foodstuffs, measured at various temperatures, and the calculated (theoretical) penetration depth z_i for microwaves of 2450 Mc/s.

Foodstuff	Meas. temp. °C	ε_r	$\tan\delta$	Penetration depth z_i (in cm) of 2450 Mc/s microwaves
Beef, raw	–15	5.0	0.15	5.8
Beef, roasted	23	28.0	0.2	2.46
Peas, boiled	–15	2.5	0.2	7.9
	23	9.0	0.5	1.5
Pork, raw	–15	6.8	1.2	0.66
Pork, roasted	35	23.0	2.4	0.18
Potatoes, boiled	–15	4.5	0.2	6.1
	23	38.0	0.3	1.44
Spinach, boiled	–15	13.0	0.5	1.42
	23	34.0	0.8	0.56
Porridge	–15	5.0	0.3	3.7
	23	47.0	0.8	0.41

[3]) Concerning the derivation of (1) and (2), see: W. Schmidt, Mikrowellengeneratoren mit abgeschlossenem Arbeitsraum zur dielektrischen Erwärmung von Nahrungsmitteln und Industrieprodukten, Elektron. Rdsch. **12**, 390 and 417, 1958, and **13**, 13, 1959; or, Microwave generators coupled to a loaded cavity for dielectric heating of foodstuffs and industrial products, Electron. Appl. **19**, 147-164, 1958/59 (No. 4).

foods are much better than might be inferred from the theoretical penetration depth given in table I.

Magnetrons

Magnetrons operate with a high efficiency and are designed for a fixed frequency. They are complete generators in themselves. The designer wishing to use a magnetron as a microwave generator is therefore virtually unconcerned with problems of high-frequency engineering such as the construction and alignment of the frequency-determining oscillatory system or the feedback system.

Magnetrons are normally fitted with some sort of demountable output connection for taking-off the power. Provided there are no significant differences in individual characteristics, the replacement of a magnetron can be reduced to a simple mechanical operation.

a

b

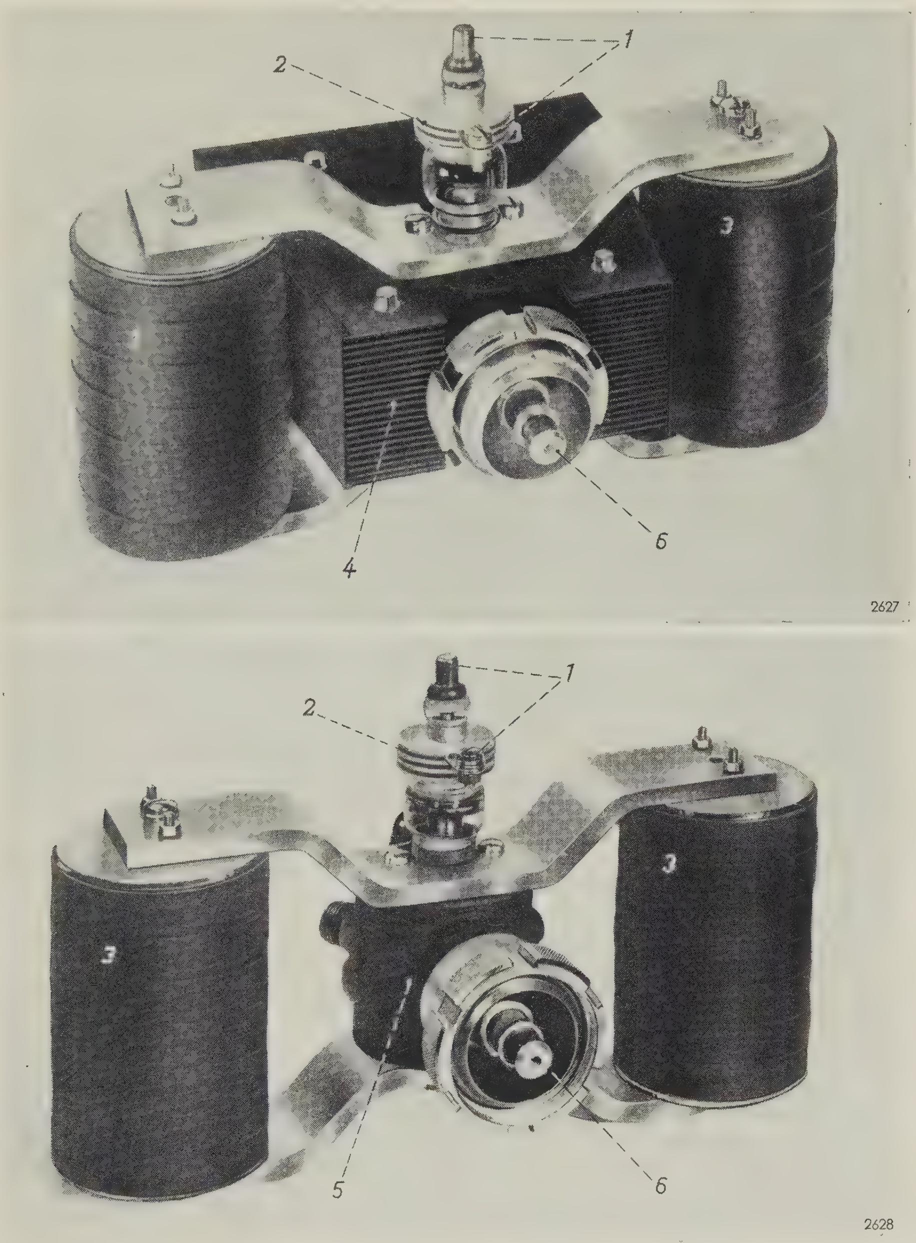

Fig. 1. Two CW magnetrons for 2 kW, 2450 Mc/s: *a*) type 7091, air-cooled and *b*) type 7292, water-cooled. *1* heater connections, the lower one also being the cathode connection. *2* cathode radiator. *3* ferroxdure magnets. *4* anode block with vanes for air cooling. *5* anode block with water cooling. *6* connection for coaxial output line (50 Ω). The inner conductor of the output connection is provided with a screw-thread, to ensure good contact with the output line even after long use at varying temperatures.

Construction of CW magnetrons types 7091 and 7292

Pulsed magnetrons, which have been used for more than twenty years in radar and electronic navigation devices, are required to meet high demands as to frequency stability, pulse shape and reliability. With a CW magnetron for RF heating the emphasis is more on such demands as high efficiency, long life, low working voltage and insensitivity to load variations. The latter point is of particular importance, since the substances heated in a microwave oven differ widely in dielectric properties, shape and size and therefore subject the magnetron to widely different loads. Constancy of frequency is of less importance, the frequency bands available for industrial purposes (and which are regulated by law in the various countries) being fairly wide.

For industrial purposes, i.e. where the high-frequency energy is used for heating, drying and sintering non-conducting substances or — as in the present case — for microwave cookery, Philips have developed two CW magnetrons, types 7091 and 7292. Microwave cookery, incidentally, was the first application of these magnetrons. Both types deliver a maximum power of 2500 watts at a frequency of about 2450 Mc/s [2]). Type 7091, which is air-cooled, was designed for ovens that may have to be moved from one place to another (*fig. 1a*). Type 7292, which is water-cooled, is intended for permanent installations (fig. 1*b*). Except for the method of cooling, the technical data for both types are identical.

Development work on a CW magnetron for an output power as high as 5 kW has recently been completed. This type, a picture of which is shown in *fig. 2*, and its possible applications, will not be dealt with here.

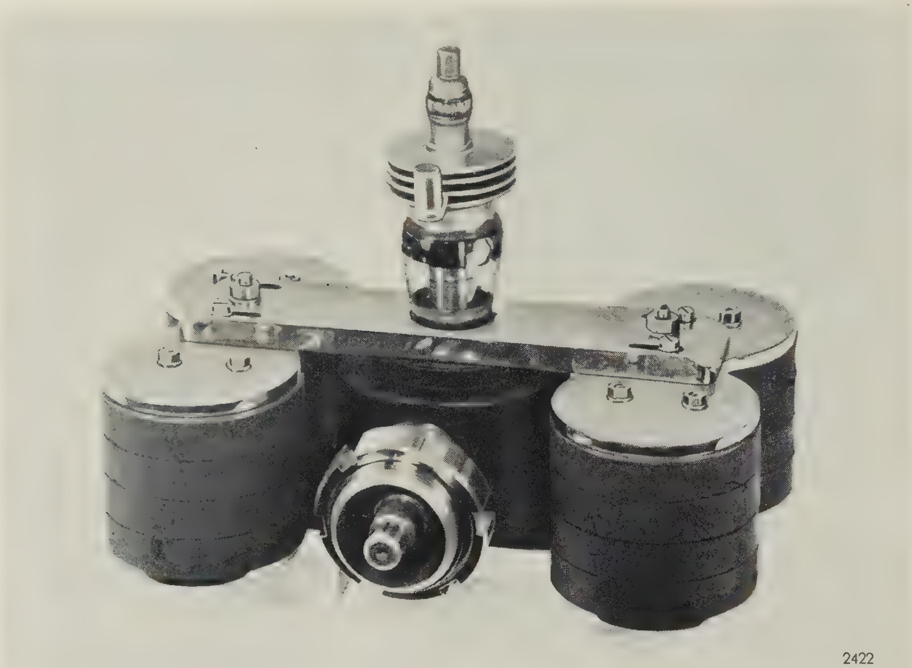

Fig. 2. CW magnetron type 55 125 for 5 kW. This magnetron also operates in the 2450 Mc/s band. The anode is water-cooled; the cathode radiator is cooled by a weak air current. The output power of 5 kW is obtained with an unsmoothed rectified voltage supply, the anode voltage being 6.5 kV and the average anode current 1.4 A. The magnetic field is provided by *four* columns of ceramic magnets. As in the 2 kW magnetrons, the power is extracted by a 50 Ω coaxial line.

The oscillatory system of the magnetrons 7091 and 7292 consists of 20 sector resonant cavities in the anode [4]). A coaxial line takes the power off by means of two balanced coupling loops (*fig. 3*).

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[4]) For a general description of the operation and design of magnetrons, see J. Verweel, Magnetrons, Philips tech. Rev. **14**, 44-58, 1952/53. See also G. A. Espersen and B. Arfin, A 3 cm magnetron for beacons, Philips tech. Rev. **14**, 87-94, 1952/53, and J. Verweel and G. H. Plantinga, A range of pulsed magnetrons for centimetre and millimetre waves, Philips tech. Rev. **21**, 1-9, 1959/60 (No. 1).

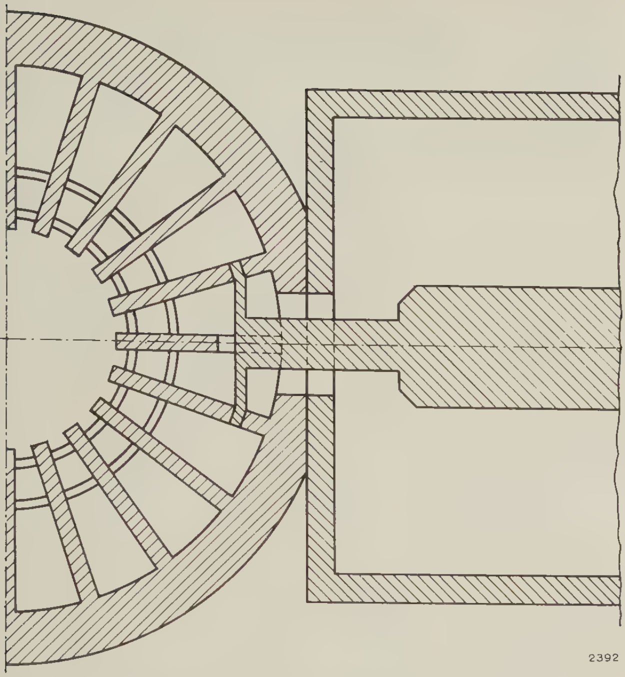

Fig. 3. Output system of types 7091 and 7292 magnetrons. The inner conductor of the coaxial output line is coupled to *two* resonant slots of the anode by a T-shaped "loop". The partitions between the resonant slots are alternately connected by two metal rings (ring strapping).

In the 2450 Mc/s frequency band it is possible to achieve high Q's for the unloaded cavity system, and therefore the coaxial output line can be permanently coupled to the magnetron. The circuit efficiency of the magnetron is then high, while the reserve of stability is still sufficient to deal with load reflections that may occur if the load is not exactly matched. To achieve this fixed coupling the system of coupling loops must link a large part of the alternating magnetic flux in a resonant cavity. However, in view of the fact that a high standing-wave ratio, as a result of load reflections, may give rise to high currents in the output line, it is necessary to use material of large cross-section for the coupling, and this makes the first requirement difficult to fulfil if a single coupling loop is used. The use of a double coupling loop provides the desired permanent coupling in the 7091 snd 7292 magnetrons in spite of the large cross-section of the loop material (which ensures good heat removal) and without any capacitive coupling with the resonant cavity, which would adversely affect operating stability.

The inner conductor of the output system of magnetrons 7091 and 7292, illustrated in fig. 3, forms part of a tapered vacuum seal. The insulation used is a ceramic, which is stronger than glass. The dielectric losses are low, even if load reflections considerably increase the standing-wave ratio in the line. The output system is fitted with a standard connecting flange.

The cathode in a magnetron is subjected to bombardment from electrons not captured by the anode [4]). These electrons absorb energy from the high-frequency field and convert this energy into heat when they return to the cathode. In CW magnetrons, then, the cathode load is not limited by the emission per unit area but by the energy density in the space between anode and cathode in relation to the surface area of the cathode. The thermionic emission is about 100 mA/cm^2, plus a considerable contribution from secondary emission. Since the energy transferred to the cathode in the form of heat by returning electrons depends on the input power and the magnitude of the load reflection, the cathode surface in CW magnetrons for industrial applications, where the load reflection may vary within wide limits, must be exceptionally strong mechanically and capable of withstanding large variations in temperature. Normal oxide cathodes are no longer adequate at high frequencies, which call for solid or sintered cathodes. Magnetrons 7091 and 7292 therefore have impregnated dispenser cathodes [5]), the emitting surface of which is a porous tungsten cylinder, impregnated with a substance that promotes thermionic emission. Such cathodes have a long life and stable emission even though subjected to high and varying temperatures. The mechanical strength of the tungsten jacket enables this kind of cathode to withstand back-bombardment as well as breakdown effects due to overloading.

A special feature is the use of a heater not in contact with the cathode proper: the cathode cylinder is thus heated only by radiation. The usual insulation of the heater — e.g. with aluminium oxide — is therefore dispensed with. In many applications, including microwave cookery in hotels and restaurants, the heater may remain switched on for hours on end, high-frequency power being taken off only now and then. Experience so far indicates that, under these conditions, this form of heater is very satisfactory. Mechanical strength is ensured by using a heater wire of considerable thickness, viz. 1.2 mm in diameter.

Operating costs are a decisive consideration where domestic and industrial apparatus are concerned. Since the magnetron represents a substantial part of the total costs, the expense entailed by its replacement must be kept as small as possible. For example, components outside the vacuum system of the magnetron should not require to be replaced when the magnetron is replaced. Moreover, in order that untrained personnel may effect replacements, the high-frequency system should require no regulation or adjustment.

In this connection the use of the ceramic ferroxdure for the permanent magnet has decided advantages. Possessing a much higher coercive force than

[5]) See R. Levi, Dispenser cathodes, III. The impregnated cathode, Philips tech. Rev. **19**, 186-190, 1957/58.

magnetic alloys, it is virtually insensitive to stray magnetic fields and to changes in the resistance of the magnetic circuit [6]). As a result, a magnetron with built-in iron pole-pieces can be removed from the magnetic circuit without any fear that the temporary demagnetization will cause permanent weakening of the induction in the air gap. The pole-pieces used in magnetrons 7091 and 7292 keep the air gap to a minimum, thereby minimizing the amount of permanent-magnet material required. In this way the magnet system using ceramic material combines the "packaged" system's advantage of low costs with the "unpackaged" system's advantage of demountability.

Ceramic magnetic material also has a certain drawback, in that its magnetic properties are more sensitive to temperature variations than those of magnetic alloys. This is not, however, a serious objection. In fig. 1 it can be seen that the ferroxdure "pillars" are connected to the magnetron system by narrow iron yokes; the effect of this is to make the time constant of the rise in temperature of the magnetic material longer than half an hour. Moreover, the final temperature rise of the magnets is only 20% of that of the magnetron itself. In view of the short periods during which the magnetron is switched on for microwave cookery, its operation is not noticeably affected by the sensitivity of the magnets to temperature variations, particularly since, in a microwave oven, fluctuations of the mains voltage and of the load impedance can cause a relatively ten-times greater variation of the output power. To compensate for changes in output power, anode-voltage regulation is necessary. In the air-cooled magnetron, type 7091, the slight influence of the temperature variations can in any case be eliminated by fitting two additional air ducts to circulate air around the magnets. In the water-cooled magnetron, type 7292, the magnetron itself rises so little in temperature that the heating of the magnets may be discounted.

Operating data and performance charts

Having considered the structural features of the CW magnetrons, we shall now examine the behaviour of the system magnetron — coaxial line — oven. The system is characterized by the way in which the frequency and the power delivered by the magnetron depend on the load impedance constituted by the coaxial line and the oven. It might be studied by drawing curves of constant frequency and constant delivered power in cartesian coordinates, the real and imaginary parts of the load impedance being plotted against one another. A more useful diagram, however, is obtained by drawing these contours in a polar diagram, with the modulus ϱ and the argument φ of the reflection coefficient plotted as radius vector and azimuth, respectively. The reflection coefficient is the ratio between the complex amplitudes of the reflected and incident waves, at any arbitrary cross-section of the coaxial line carrying the power from the magnetron. The position of this "reference plane" is usually chosen at the connecting flange of the magnetron. The modulus ϱ is determined by measuring the standing-wave ratio σ in the coaxial line; the relation between ϱ and σ is given by the formula $\sigma = (1+\varrho)/(1-\varrho)$. The argument φ is related in a simple manner to the distance $\Delta l_{\min}$ from the reference plane to the nearest minimum in the standing wave, according to the expression: $\Delta l_{\min}/\lambda = \frac{1}{4}(1-\varphi/\pi)$, where λ is the wavelength in the coaxial line. To make the diagram simpler to use, it is convenient to plot, as in *fig. 4*, circles for constant values of σ instead of for constant values of ϱ. Since σ runs from 1 for $\varrho = 0$ to $\sigma = \infty$ for $\varrho = 1$, the value of σ rapidly increases as the circle grows larger. Also, the diagram give values of $\Delta l_{\min}$, expressed in terms of λ, instead of values of φ itself. At a constant magnetic field and constant anode current, the values of σ and $\Delta l_{\min}/\lambda$ can be measured for arbitrary values of the load impedance (which need not itself be known). Each measurement produces a point in the diagram. The corresponding values of the frequency and output power are also measured. By doing this for various values of the load impedance, and by joining-up the points of equal power and also those of equal frequency, we obtain the Rieke diagram for the magnetron. Fig. 4 gives the diagram for types 7091 and 7292. The diagram relates to an operating point corresponding to 2000 W, that is to values of magnetic field and anode current such that, given ideal matching (centre point of diagram, $\sigma = 1$), the output power is 2000 W. The possible application and merits of a CW magnetron can now be assessed by noting the relation between the various quantities depicted in the diagram.

It is seen that as the power is increased, the power contour moves towards the upper right of the diagram. The operating point of the magnetron must not, however, enter the hatched area known as the "sink region", i.e. the region of instability, where the magnetron no longer oscillates properly. The frequency contours also converge upon this region,

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[6]) See Philips tech. Rev. **13**, 194-208, 1951/52 and **16**, 141-147, 1954/55.

indicating that here the frequency, too, is highly unstable. Opposite this "electronic instability limit" can be seen the "thermal instability limit", *Th*. If this is exceeded, the cathode will be overheated due to back-bombardment by returning electrons. mined by the minimum distance between the centre point and the boundaries of the dangerous regions, is then as high as it can be. As regards the type 7091 and 7292 magnetrons, this is the situation at the 2 kW setting.

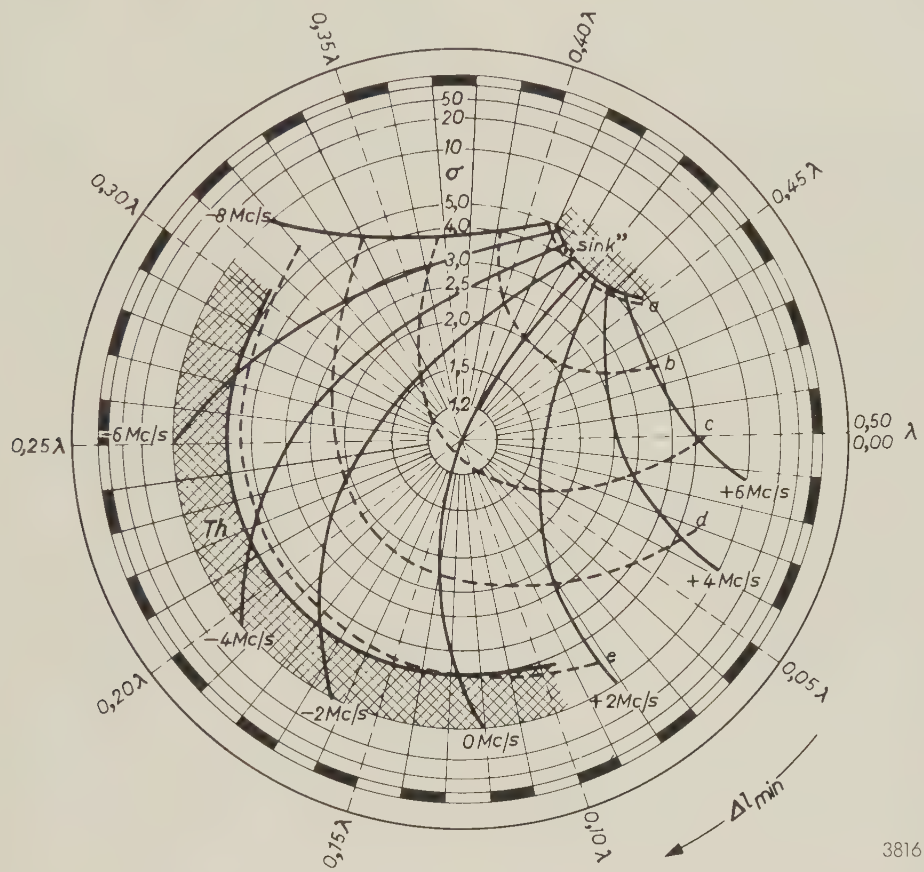

Fig. 4. Rieke diagram of a type 7091 or 7292 magnetron. The circles are contours of constant standing-wave ratio σ, the values being indicated. Around the periphery are set out the values of Δl_{min}, being the distance from the reference plane (through the connecting flange of the magnetron) to the first minimum or node of the standing wave, expressed in terms of the wavelength λ in the coaxial output line. The diagram contains contours of constant frequency (solid curves) and of constant output power (dashed curves). The letters *a*, *b*, *c*, *d* and *e* on the dashed lines refer to the table, where the corresponding values of output P_o and anode voltage U_a are given. The diagram holds for an operating point of 2000 W, i.e. the output power is 2000 W when the load impedance is a matched termination, giving a standing-wave ratio of $\sigma = 1$ (centre point of diagram). The hatched region top right is the region of electronic instability, called the "sink"; opposite to it is the region of thermal instability *Th*. When the magnetron is in operation, σ must never be so high as to bring the operating point into one of these regions.

	a	*b*	*c*	*d*	*e*
P_o (W)	2500	2250	2000	1500	1000
U_a (kV)	4.7	4.6	4.5	4.4	4.3

The anode, too, will be overheated because too little power is then withdrawn from the magnetron as a result of strong reflection from the load impedance. The aim is to design the whole magnetron system so as to keep these forbidden regions as far apart as possible and also to ensure that the midpoint of the diagram lies midway between the electronic and thermal instability limits. The maximum permissible standing-wave ratio, which is determined by the minimum distance between the centre point and the boundaries of the dangerous regions, is then as high as it can be.

Fig. 4 also indicates the extreme values between which the frequency will adjust itself if the standing-wave ratio is, say, 1.6. The circle for $\sigma = 1.6$ touches the contours for $+ 2$ Mc/s and $- 2$ Mc/s, so that the operating frequency will be within the 2450 ± 2 Mc/s band. The microwave frequency band allocated for industrial applications is 2400-2500 Mc/s in most countries (2350-2450 in Germany). Owing to the spread in properties between magne-

trons as manufactured, it is always possible to select individual specimens having frequencies suited to the local conditions.

It is most important that the operating point should not enter the sink region, as this can very quickly cause damage to the magnetron. The consequences are not so serious if the boundary of the thermal instability region is crossed. The position of the two danger zones depends, of course, on the anode current; they move inwards as the anode current increases, in which case the maximum permissible standing-wave ratio is reduced.

A direct voltage is commonly used for the anode of a CW magnetron. Magnetrons can also operate, however, with an alternating anode voltage, or with a rectified but unsmoothed alternating voltage, and the latter is in fact used in this case. With a full-wave rectified, unsmoothed voltage the ratio of the peak anode current to the mean value is about 2.5; the sink then lies outside the circle for $\sigma = 4$. With an AC supply the permissible value of σ is smaller. If a smoothed rectified voltage were used — in which case the ratio of peak to mean current would be about 1 — the limit of electronic stability would lie further from the centre of the Rieke diagram, and on the face of it the permissible value of σ might then be higher. The objection here, however, is that at values of σ higher than 4 or 5 (in other words, with a reflection of more than 50% of the power), large concentrations of energy may occur at places of maximum field-strength, with consequent danger to the output line contacts and the vacuum seal of the output coupling. Standing-wave ratios higher than 4 or 5 are therefore ruled out, so that there is nothing to be gained from smoothing. This cuts out the expense of smoothing capacitors, and thus helps to keep down the price of the cooker.

Table II. Principal data for magnetrons 7091 and 7292, valid for ideal matching (operation at 2 kW) and provisional data for 5 kW magnetron type 55 125.

Type of magnetron	7091 and 7292	55 125
Anode voltage	4.5 kV	6.5 kV
Mean anode current	0.75 A	1.4 A
Maximum peak anode current	2.1 A	2.4 A
Output power	2000 W	5000 W
Maximum permissible standing-wave ratio σ_{max}:		2.5
sink (electronic limit)	4.0	
thermal limit	5.0	

In any case, smoothing would involve the extra danger that sparking and flashover effects might develop, as a result of capacitor discharges, into serious electrical breakdowns. The use of two-phase or three-phase rectifiers, with no smoothing, is therefore to be recommended for supplying a normal microwave cooker operating at 2 kW.

Tables II and *III* give some general data on the 7091 and 7292 magnetrons, and some performance data for the case of ideal matching. For comparison, the provisional data for the 5 kW magnetron are included.

Table III. General data for CW magnetrons 7091 and 7292, and provisional data for type 55 125.

Type of magnetron	7091	7292	55 125
Power extraction system	$1\frac{5}{8}''$ coaxial line; 50 Ω		
Cooling of anode block	Air, approx. 1.7 m³/min	Water, at least 0.5 l/min, depending on inlet temp.	Water, approx. 2.5 l/min, depending on inlet temp.
Cooling of cathode radiator	Weak air current		
Max. temperature of anode block	125 °C	125 °C	125 °C
Max. temp. of cathode radiator	180 °C	180 °C	180 °C
Heater voltage: upon switching-on	5.0 V (+5%, —10%)		5.5V(+5%,—10%)
in normal operation	2.0 V		3.5 V / 1 V
Heater current: upon switching-on	32 A		66 A
in normal operation	18 A		52 A / 28 A
Warm-up time	120 s		240 s

The oven

To build a microwave cooker using the magnetron described, the first question to be decided concerns the shape of the oven, i.e. the space in which the food is exposed to the microwaves. The aim is to achieve in this space a uniformly distributed energy density, in order that the foodstuffs introduced shall be uniformly heated. If we choose a rectangular shape, the space will then act as a resonant cavity which, fed with energy through a coupling system, can be made to oscillate if the wavelength in vacuo λ_0, corresponding to the magnetron frequency f (i.e. $\lambda_0 = c/f$, where c is the velocity of light), and the side lengths a_x, a_y and a_z satisfy the following condition (m, n and p are integers):

$$\lambda_0 = 2\Bigg/\sqrt{\left(\frac{m}{a_x}\right)^2 + \left(\frac{n}{a_y}\right)^2 + \left(\frac{p}{a_z}\right)^2} \quad . \quad . \quad . \quad (3)$$

This condition applies strictly only to an ideal resonant cavity with no damping and with no space charge [7]). In reality, however, all resonant cavities possess a certain damping, as a result of which their resonance curves show broad maxima, the more so if substances are introduced in them — as in the oven — which further increase the damping. Condition (3) need not, therefore, be exactly fulfilled; provided only the sides are longer than $\frac{1}{2}\lambda_0$, there will always be integers m, n and p in respect of which (3) is satisfied with sufficient accuracy. Such a set of m, n and p values is met by a field distribution consisting of a pattern of standing waves having m, n and p half-wavelengths (not to be confused with λ_0) in the three directions. If the sides are much longer than $\frac{1}{2}\lambda_0$, there will be many sets of values of m, n and p for which condition (3) is adequately satisfied. In such an oven, then, there can exist numerous modes of oscillation at the same time, and they are all simultaneously excited provided that the boundary conditions are fulfilled at the position of the coupling with the exciter waveguide. Thus, if the dimensions of the oven are large compared with $\frac{1}{2}\lambda_0$, superposition of the various oscillation modes leads to a more or less uniform distribution of energy in the oven. If no further measures are taken, however, non-uniformity will nevertheless appear over larger distances. The reason for this may be unbalanced coupling with the energy source, irregularities in the walls (e.g. the oven door), the presence of trays for putting the food on, and so on. When the foodstuffs are placed in the oven, they also affect the field distribution. Owing to the absorption of energy the resultant field is composed of wave trains which, depending on whether or not they have passed through the absorbent substance, transport energy of differing density. Added to this is the partial reflection of the waves from the surface of the substance; how large this reflection is depends on the dielectric constant of the substance. It must also be remembered that the excitation frequency may vary slightly because of the spread in characteristics between individual magnetrons. The desired uniformity in the distribution of energy in the oven must be assured over the whole range of excitation frequencies. We shall now consider the measures to be adopted to this end.

The broadening of the resonance peaks as a result of damping also tends to stabilize the field distribution, and hence the load impedance of the magnetron. The latter is of considerable importance, since one of the primary conditions to be met if the magnetron is to be interchangeable is that the empty oven shall represent the same load for all magnetrons of the type used. It should consequently yield approximately the same operating point in the Rieke diagram, irrespective of the frequency of the particular magnetron and without the need to adjust the plunger in the matched waveguide, which acts as a matching transformer, between the coaxial line from the magnetron and the oven. The damping in an oven measuring $44 \times 40 \times 36$ cm should be at least equivalent to 100 cm^3 of water. Since all parts of the oven in which high-frequency currents flow give rise to losses, every oven possesses a certain amount of damping, but this is adequate only if the walls consist of a material whose resistance is not unduly low — e.g. V2A steel — and provided also that the oven contains such components as reflector plates and bars forming a hot grill. The damping can be increased if the oven trays for putting the food on are made of dielectric materials like glass or certain plastics, which give rise to greater losses than metal trays. They constitute a basic load which is sufficient to allow the cooker to be left switched on when the oven is empty. When there is food in the oven, only a few per cent of the consumed power is lost in these trays, their dielectric losses being much smaller than those of the food.

Fig. 5 shows two sections through the oven of a microwave cooker. The oven contains a tray for the food, a zig-zag heating element for grilling and a reflector plate. The purpose of the reflector is to promote a homogeneous energy density in the oven, its principal action being to offset the irregularity

[7]) The derivation of (3) is given in the first article quoted in footnote [3]).

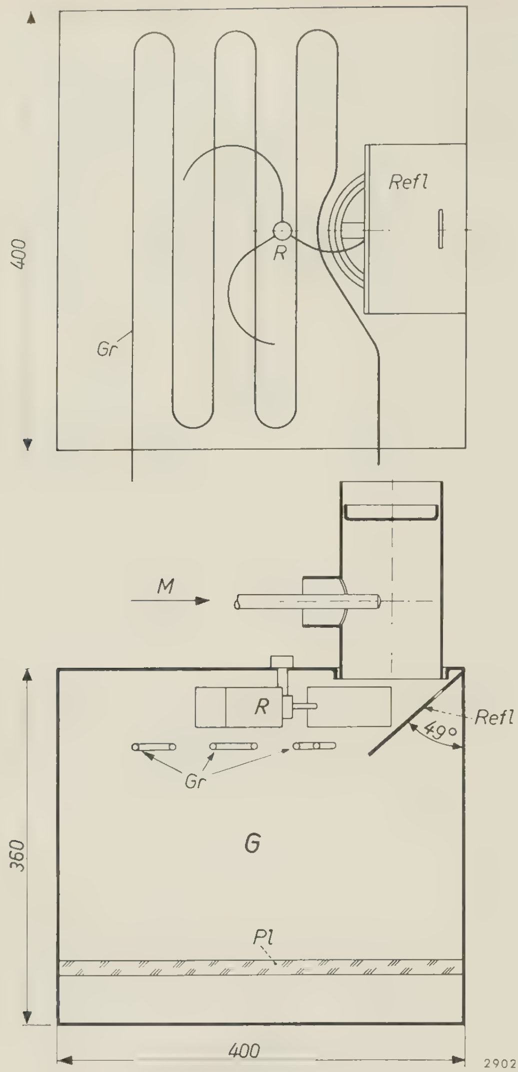

Fig. 5. Two sections through the oven of an experimental microwave cooker. *M* coaxial line from magnetron. *G* oven. *Refl* reflector. *R* field stirrer. *Gr* grill element. *Pl* tray for carrying the food. Dimensions in mm.

caused by the asymmetrical connection of the matched waveguide (see below). The same result can be obtained by fitting the internal edges of the oven with oblique metal strips.

The effect of all these measures and the best position of the reflector plates can only be found by experiment. For this purpose, 25 small dishes, each containing 50 cm^3 of water, were placed in an experimental oven. The rise in the temperature of the water in these dishes within a certain time gives qualitative and quantitative indications regarding the distribution of the energy density, averaged over time, in the plane where the dishes are situated. *Fig. 6a* shows the result of an initial experiment. The marked rise at the right of the oven is due to the fact that the matched waveguide is not connected symmetrically. There was a practical reason for this, namely that, in addition to this waveguide, room had to be found on the oven for the magnetron and a fan as well. Fig. 6*b* illustrates the improvement effected by introducing a reflector provided with a slit, as shown in fig. 5. The energy density can be made still more uniform — or at least its time average — by constantly varying its distribution. This may be done by varying certain quantities that affect the boundary conditions for the field distribution. Since the frequency of the magnetron can only be altered within narrow limits, the only possibility is to alter the geometry of the oven, e.g. by making the walls themselves, or special reflector plates, undergo periodic movement. The oven represented in fig. 5 contains a rotating blade reflector called a "field stirrer". Fig. 6*c* shows the density distribution of the dissipated energy after the stirrer has been given a suitable shape and position in the oven, again found by experiment. One might also, of course, homogenize to some extent the heat development in the food by making the oven tray rotate.

Once a uniform distribution of energy has been achieved by these measures, it is disturbed again by the absorption and reflection of energy that occurs as soon as food is introduced. It is therefore virtually impossible to achieve a homogeneously dense distribution of energy in the oven for any arbitrary content. In practice, however, it is found that sufficiently uniform heating is obtained without the radiant energy density being exactly homogeneous, the reason being that heat conduction in the food has an equalizing effect.

A door is required that gives easy access to the oven. When closed it must shut-in the microwave energy, and this raises problems concerning the door contacts. Chinks in the oven wall allow microwave energy to escape and also distort the field distribution inside. The first step is to try by mechanical means to ensure good electrical contact in the door joints, e.g. by arranging a series of contact springs around the opening. At high frequencies it is necessary to use very reliable contacts, but as they inevitably get dirty it is difficult to keep them functioning well over a long period. The second possibility of making the door "high-frequency tight" consists in using quarter-wave slots. Two such slots are used, opposite to each other and both $\lambda/4$ deep (in this case 31 mm deep at $f = 2450$ Mc/s, $\lambda = 12.5$ cm); together they form a waveguide $\lambda/2$ long, short-circuited at one end (*fig. 7a*). As a result of reflection a standing wave appears in these slots, the voltage and current distribution of which are shown in fig. 7*b*. As the current in the middle

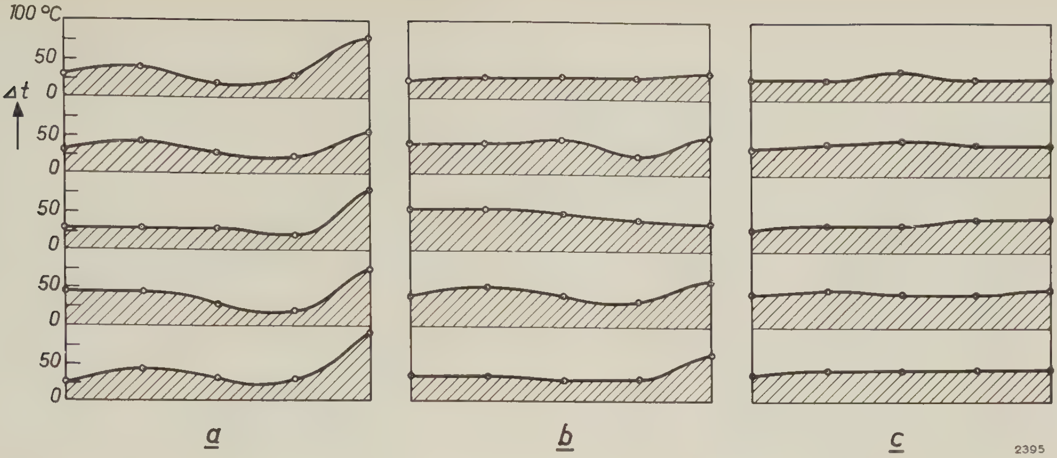

Fig. 6. Distribution of energy density in the oven of an experimental microwave cooker. The three diagrams a, b and c relate to the same horizontal section through the oven at the situation of the food. At five points along each of five straight lines in this cross-section is plotted the temperature rise in twenty-five dishes, each containing 50 cm³ of water. In each case, a, b, c, the cooker was switched on for the same time.
a) Original distribution.
b) The distribution has been made more uniform by introducing a reflector plate containing a slit (see fig. 5).
c) The time-averaged energy distribution has been made very uniform by the use of a "field stirrer".

is zero, the contact at that position need not be perfect and that is where we can situate the join between oven wall and door. This produces the effect — at least in theory — of a space closed without joins, and one may therefore count on insensitivity to corrosion and dirt.

In practice the $\lambda/4$ slots are not in themselves sufficient, particularly not when the oven is empty and there are high RF currents flowing in the walls. The slots should therefore be combined with an effective mechanical contact, as illustrated in

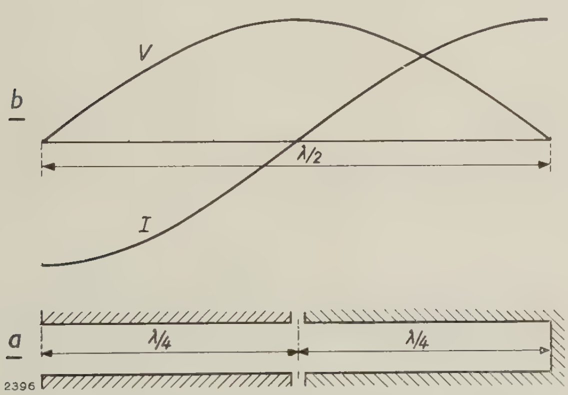

Fig. 7. Illustrating how the use of quarter-wave slots prevents the escape of high-frequency energy.
a) Two opposing slots, each $\lambda/4$ deep, constitute a $\lambda/2$ waveguide short-circuited at one end.
b) Voltage (V) and current (I) amplitudes along the $\lambda/2$ waveguide. At the position where $I = 0$, a poor electrical contact is of no consequence.

fig. 8. Here, however, the existing mechanical contact between door and housing at the right had to be improved by contact springs, which are not shown in the drawing.

The wall currents being strongest when the oven is empty, the door contacts are then subjected to the severest load and there is then a greater chance

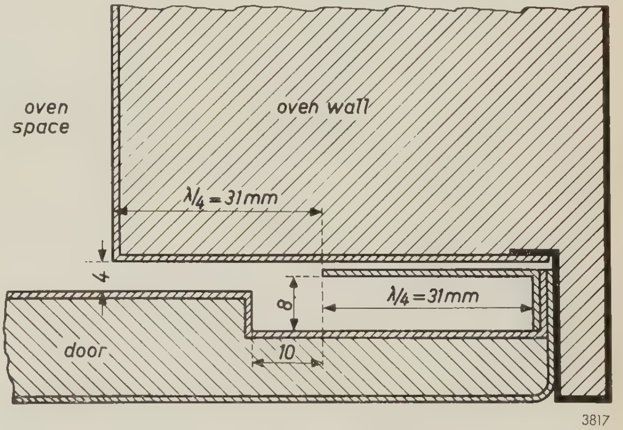

Fig. 8. The application of $\lambda/4$ slots to prevent the escape of microwave energy through the joins in the oven door. In practice it turns out that it is still advantageous to use contact-springs. These are not shown in the drawing.

of damage being done to the contacts and of microwave escaping. It should also be remembered that the microwave energy may not always be uniformly distributed over the whole circumference of the door but may be concentrated, radiating from corners or hinges if the construction is imperfect.

Construction and circuitry of a microwave cooker

To conclude we shall now touch on the actual construction of an experimental microwave cooker, and also discuss briefly the power supply circuit. A microwave cooker intended for a wide market

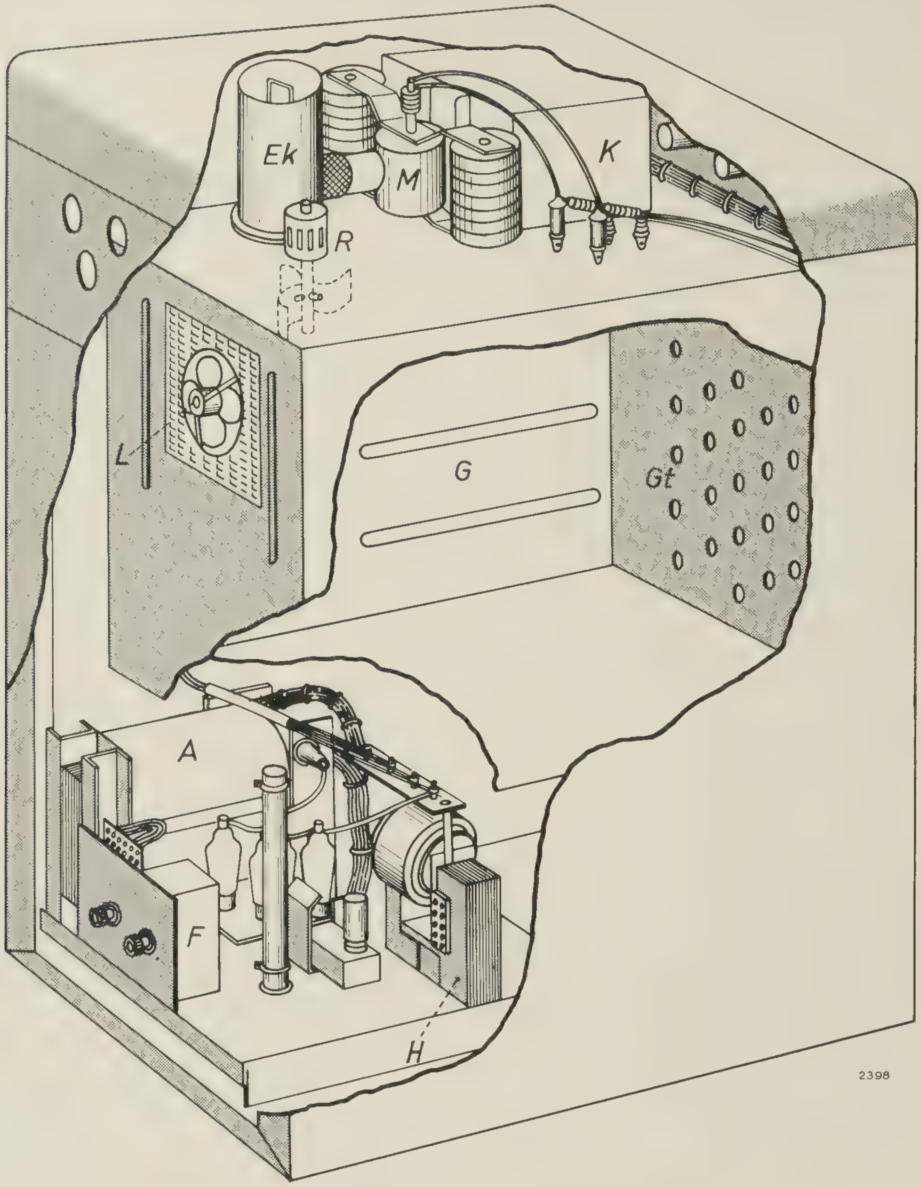

Fig. 9. Cutaway view of a microwave cooker. *M* magnetron. *K* cooling fan. *Ek* coupling waveguide. *R* field stirrer. *G* oven. *L* air extractor. *Gt* oven door. *A* anode-voltage transformer. *F* suppressor filter. *H* heater-current transformer (the secondary of which is at high tension and is correspondingly insulated).

and which will be handled by untrained users (cooks and housewives) must be reliable and easy to operate. It must therefore be provided with safety devices to prevent overloading and to exclude the risk of damage or accidents due to mistakes in operation.

Fig. 9 gives a somewhat simplified cut-away view of a microwave cooker, seen from the back, that could be installed in a restaurant or private kitchen. As can be seen, the oven is about half-way up, at the same level as in an ordinary cooker. The magnetron *M*, with its coaxial output line and the matched waveguide *Ek*, is mounted on top of the oven. Here, too, are accommodated the cooling fan *K* and the motor for the field stirrer *R*. The rear wall of the oven is fitted with an extractor fan *L*. The oven door is provided with holes through which fresh air can enter and which make it possible to watch the food while it is cooking. Interior lighting, not shown in fig. 9, is then necessary. (There is no significant escape of microwave energy either through these holes or through the air extractor.) The oven may also be fitted with a grill element which, as mentioned, serves as part of the main load and also provides thermal radiative heating to give the customary brown crust. Food cooked in a microwave oven does not change much in appearance; in order, therefore, to ensure adequate cooking and to prevent overcooking it is desirable

to provide the cooker with a built-in timer. This is mounted, together with various switches and pilot lamps, on a panel above the oven door.

The power pack is located under the oven. The position of the valves, transformers and other components can be seen in fig. 9. Further particulars of the circuit are given in *fig. 10.* A filter is inserted in the mains leads to suppress interference from transients that may be generated by the magnetron when it is switched on. When the main switch S_1 is turned on, current flows to the heaters of the magnetron and rectifier valves, and the fan K for cooling the magnetron, the stirrer R and the air extractor L are started up. Block H contains the heater-current transformer for the magnetron; the secondary is at high tension and is correspondingly insulated, and therefore the heater current is regulated at the primary side. Two minutes after S_1 has been switched on, the time relay T closes the safety switch V, enabling the anode voltage for the magnetron to be switched on with S_2. The time the oven is to operate is preset with the timer t. In series with S_2 there are two other safety switches Tk and Lk. The door switch Tk cuts off the magnetron if the door is opened; if one were to put one's hand into the radiation field, damage could be done to internal tissues. Switch Lk opens if the temperature of the magnetron is too high, indicating that the air or water cooling is not functioning properly.

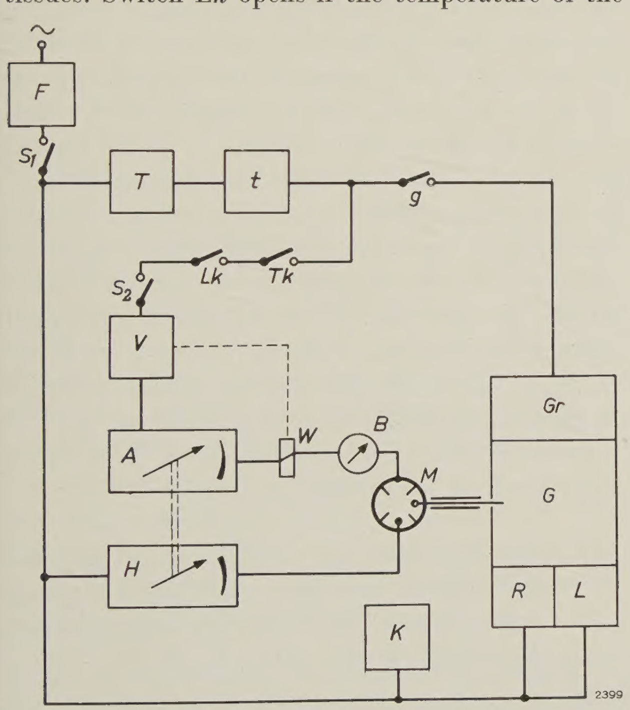

Fig. 10. Block diagram of a microwave cooker. F suppressor filter. S_1 main switch. T time relay. t timer. S_2 switch for magnetron high tension. Lk and Tk safety switches, which can close only when the magnetron temperature is not too high and the oven door is closed. V anode-voltage switch. A power pack supplying anode voltage. H filament-current transformer. W overload safety device. M magnetron. B ammeter for anode current. K cooling fan for magnetron. G oven. R field stirrer. L air extractor. Gr grill element. g switch for Gr.

Block A contains the anode voltage transformer, which is regulated at the primary side, and the rectifier valves. In connection with the Rieke diagram (fig. 4) it was mentioned that the magnetron may be fed with an unsmoothed, rectified voltage. The ratio between the peak and mean values of the anode current affects the permissible value of the standing-wave ratio σ, and this is taken into account in the design of the high-tension and rectifier section. The HT, after being switched on, should be turned up very gradually, otherwise the taste of delicate foodstuffs might be spoilt by sudden overheating. In blocks A and H (fig. 10) it is indicated symbolically that the heater voltage is gradually reduced as the anode current is turned up; if this were not so, back-bombardment would overheat the cathode. The meter B in fig. 10 is an ammeter for the anode current; it provides a check on the power delivered by the magnetron and thus simplifies the operation of the cooker. For practical purposes all the dial need contain is a mark indicating the maximum permissible deflection of the needle. If the anode current becomes too high, e.g. as a result of mains fluctuations, the relay W shuts off the high tension via the safety switch V.

The oven G further contains a grill element Gr, which is operated by a separate switch g but can also be brought into action by the timer.

The microwave cooker illustrated in fig. 9 is only an example. A continuous-feed oven might equally well be built, which could serve for heating or cooking large numbers of the same dishes in big kitchens or canteens. The 5 kW CW magnetron mentioned earlier (fig. 2) might be used with advantage here. A continuous oven lends itself well to automation, in which form microwave heating could also be used in industry, e.g. for drying wood, paper and textile products, for welding and sintering plastics and for numerous other purposes [8]). Compared with the traditional method of (dielectric) RF heating, the microwave method offers the advantage of a greater concentration of power in the workpiece. Compared with infra-red heating, microwaves have the advantage of great depth of penetration, giving effective heating from inside outwards.

Summary. After a review of the physical principles of dielectric heating in a microwave radiation field, a CW magnetron is described which is capable of delivering 2 kW continuous output at 2450 Mc/s. (Reference is also made to a recently-developed 5 kW CW magnetron.) The 2 kW magnetron is made in two

[8]) See e.g. W. Schmidt, Mikrowellengenerator zur dielektrischen Erwärmung und Trocknung nichtmetallischer Bahnen und Folien, Elektron. Rdsch. **13**, 359, 1959 (No. 10).

versions, air-cooled and water-cooled, and is especially suited for the heating of foodstuffs in a resonant cavity (microwave cookers). The magnetron has an impregnated dispenser cathode, delivers its power through a double coupling loop to a coaxial line, and is equipped with a ferroxdure magnet. The characteristics of the magnetron are discussed with reference to its Rieke diagram.

When used in a microwave cooker the magnetron is required to operate under a widely varying load impedance. The oven of the cooker must be so designed as to minimize load reflections, which give rise to standing waves in the magnetron output line. A uniform field distribution in the oven is achieved by means of reflector plates and a "field stirrer". It is important to provide for adequate damping in the oven, particularly when there is no food in it. Quarter-wave slots are used to prevent microwave energy escaping through the door joints. Finally the construction and circuitry of an experimental microwave cooker are discussed.

ABSTRACTS OF RECENT SCIENTIFIC PUBLICATIONS BY THE STAFF OF N.V. PHILIPS' GLOEILAMPENFABRIEKEN

Reprints of these papers not marked with an asterisk * can be obtained free of charge upon application to Philips' Electrical Ltd., Century House, Shaftesbury Avenue, London W.C. 2, where a limited number of reprints are available for distribution.

***2753:** J. Smit and H. P. J. Wijn: Ferrites: physical properties of ferromagnetic oxides in relation to their application (Philips Technical Library, 1959, XIV + 369 pp., 244 figures).

See the book notice printed below (p. 104).

***2754:** H. Bremmer: Mode expansion in the low-frequency range for propagation through a curved stratified atmosphere (J. Res. Nat. Bur. Standards **63 D**, 75-85, 1959, No. 1).

The expansion cited in the title is particularly useful when ionospheric propagation at low frequencies is considered. The complex problem dealing with two media, viz., a homogeneous earth and a surrounding stratified atmosphere, leads to intractable expressions. However, as the influence of the earth may be accounted for by an approximate boundary condition at the earth's surface, the problem is reduced to that of the outer medium only. The coefficients of the mode expansion for this simplified problem are derived while taking into account the earth's curvature; however, the latter proves to be negligible under very general conditions. The expansion derived is wanted in particular when the influence of a gradual transition in the electron density with height at the lower edge of the ionosphere is studied.

***2755:** W. J. Oosterkamp and J. Proper: The water equivalence of "Mix D" phantom material for soft X-rays (Brit. J. Radiol. **32**, 560, 1959, No. 380).

Correction to No. **2645**.

2756: H. F. Hameka: Calculation of the magnetic susceptibility of methane (Physica **25**, 626-630, 1959, No. 7).

The magnetic susceptibility of methane is calculated by employing molecular orbitals which are constructed from gauge invariant atomic orbitals. The result is $\chi = -13.7 \times 10^{-6}$; the agreement with the experimental value $\chi = -12.2 \times 10^{-6}$ is satisfactory.

2757: W. van Gool and A. P. D. M. Cleiren: Influence of hydrogen on the red ZnS-Cu fluorescence (J. Electrochem. Soc. **106**, 672-676, 1959, No. 8).

Self-coactivated ZnS-Cu phosphors were made by firing in different atmospheres. When H_2S/H_2 mixtures were used, the red fluorescence decreased with increasing amounts of hydrogen. With Ar/S_2 or with N_2/S_2 atmospheres no red fluorescence was obtained. These experimental results can be summarized by stating that, in order to obtain the red fluorescence, hydrogen must be incorporated into the phosphor and the sulphur pressure must be sufficiently high. The hydrogen either forms a part of the red center or it destroys or replaces a killer center that prevents the occurrence of red fluorescence when hydrogen is absent. In connection with the high sensitivity of the red fluorescence to small amounts of impurities it is suggested that the concentration of the red centers is much smaller than the amount of incorporated copper.

2758: H. Koelmans and C. M. C. Verhagen: The fluorescence of binary and ternary germanates of group II elements (J. Electrochem. Soc. **106**, 677-682, 1959, No. 8).

The fluorescence of binary and ternary germanates of Ca, Sr, Ba, Mg and Zn with different activators was investigated. Germanate phosphors activated with Pb, Ti and Mn are described. The ternary composition triangles are given together with the X-ray powder-diagrams of 23 hitherto unknown germanates.

2759: N. W. H. Addink: Determination of the transition probability (reciprocal of lifetime) of excited atoms and ions from spectro-analytical data and the importance of lifetime values in spectrochemistry (Spectrochim. Acta **15**, 349-359, 1959, No. 5).

The purpose of this investigation was to discover why some of the spectral lines used in the method of spectrum analysis by means of direct-current arc discharge do not meet the requirements of reproducibility. While studying the origin of these lines it was found necessary to calculate their transition probability (reciprocal of lifetime), which proved that a relatively long lifetime is responsible for emission disturbances (collisions of the second kind).

2760: H. J. L. Trap and J. M. Stevels: Physical properties of invert glasses (Glastechn. Ber. **32 K**, VI/31-VI/52, 1959, No. 6).

The conventional silicate glasses are characterized by an irregular spatial Si-O network, in the interstices of which a number of network modifiers are situated. The physical properties of these glasses are mainly determined by the behaviour of this network. However, going to a rather low silica content, the coherence of these glasses and their physical properties can no longer be determined by the spatial Si-O network, since only rather short Si-O chains are present. The cations determine the behaviour of the glass (invert glasses). It is shown that in invert glasses certain properties (viz. those which are related to short-range phenomena, such as dielectric and mechanical losses, viscosity, coefficient of expansion) vary with composition in a direction opposite to that in conventional glasses. Properties reflecting an average overall situation (dielectric constant, refractive index) vary in the same direction as in conventional glasses. It is shown that the transition from conventional glasses to invert glasses takes place at compositions where the average number of non-bridging oxygen ions per SiO_4 tetrahedron is two. Consequently this criterion may be used to determine which fraction of "intermediates" is present in the form of network modifiers and network formers.

2761: J. M. Stevels: Netzwerkfehler in kristallinischem und glasigem SiO_2 (Glastechn. Ber. **32**, 307-313, 1959, No. 8). (Network imperfections in crystalline and vitreous SiO_2; in German.)

Crystalline and vitreous SiO_2 almost always contain network imperfections. Their concentration, however, is often so small that they are undetectable by the methods of chemical analysis. There are also network imperfections which by their very nature cannot be detected in this way. Modern physical methods are now available (dielectric loss measurement at low temperatures, paramagnetic resonance measurements and optical absorption methods) which can give not only some estimate of the concentration but also some idea of the kinds of imperfection present. Comparison of the network imperfections before and after irradiation with electromagnetic waves (short-wave U.V., X-rays or γ-rays) or neutrons, can lead to some idea of the "reactions" brought about by such radiations in crystalline and vitreous silica.

2762: C. J. Bouwkamp: Interaction of two crossed cylinders in the presence of Van der Waals forces (Nieuw Arch. Wisk. **7**, 66-69, 1959, No. 2).

Calculation of the Van der Waals interaction energy of two crossed infinite circular cylinders in terms of their radii and separation.

2763: H. C. Hamaker: A note on ANOVA in the transistor industry (Industr. Qual. Control **16**, 12-14, 1959, No. 1).

Discussion between the author and A. W. Wortham on an application of variance analysis to certain problems in transistor applications. The discussion centers around the problem of how to deal with one apparently discrepant observation, a so-called outlier.

2764: A. H. Boerdijk: Contribution to a general theory of thermocouples (J. appl. Phys. **30**, 1080-1083, 1959, No. 7).

Application of thermodynamics of irreversible processes to a thermocouple of which (a) the bars have an arbitrary shape, (b) the properties of the materials are arbitrary functions of temperature, and (c) the composition is, under certain restrictions, inhomogeneous and anisotropic, leads through introduction of a single place coordinate to two nonlinear differential equations describing the stationary distribution of temperature and electrical potential. Output powers and efficiencies are expressed in terms of the temperature gradients in the bars. The maximal values of the efficiencies obtained by variation of the shape of the bars are independent of the shape. Upper bounds of the efficiencies attainable by stationary thermoelectric conversion are derived. If the shape of the bars is restricted to general cylinders and truncated wedges or cones, the transient behaviour is described by two partial differential equations which contain two independent variables

only. A periodic ripple in the electrical current has the same effect as a decrease of the electrical conductivities of the materials.

2765: J. S. C. Wessels: Studies on photosynthetic phosphorylation, III. Relation between photosynthetic phosphorylation and reduction of triphosphopyridine nucleotide by chloroplasts (Biochim. biophys. Acta **35**, 53-64, 1959, No. 1).

The photochemical reduction of TPN by isolated chloroplasts was investigated. A comparison of the rate of TPN reduction with that of photosynthetic phosphorylation provided evidence that the generation of ATP in the presence of vitamin K_3 or FMN is not coupled with the reoxidation of TPNH by the oxidized product of the photolysis of water. Photosynthetic phosphorylation could proceed unimpaired under conditions in which the chloroplasts had lost their ability to reduce TPN. On the other hand TPN reduction could be considerably stimulated by a chloroplast extract which did not affect photosynthetic phosphorylation. These results are discussed in relation to the recent finding that the reduction of TPN by chloroplasts is accompanied by ATP formation.

2766: M. J. Sparnaay: The interaction between two cylinder-shaped colloidal particles (Rec. Trav. chim. Pays-Bas **78**, 680-709, 1959, No. 8).

The theory of the stability of lyophobic colloids, as given by Derjaguin and by Verwey and Overbeek for the flat-plate model or the sphere model of colloidal particles, is applied to cylinder-shaped colloidal particles. Anisometry was taken into account by considering the interaction between two parallel particles and between two particles in a crossed position. Mathematical expressions are given for the repulsive and the attractive potential energy in these two cases. It can be inferred from these expressions that the behaviour of two parallel cylinders is intermediate between the behaviour of two flat plates and two spheres, whereas two crossed cylinders behave in much the same way as two spheres.

Now available

J. Smit and H. P. J. Wijn: Ferrites: physical properties of ferromagnetic oxides in relation to their application (Philips Technical Library, 1959, XIV + 369 pp., 244 figures).

In recent years the most important developments in magnetic materials have been in the field of magnetic oxides. This book gives the reader an introduction to ferrites, that is to say, the magnetic oxides containing iron as their main component. In the many theoretical problems treated, the authors make use of simple physical models rather than rigorous mathematical methods. In view of the large and growing number of applications of ferrites in electronics and electrical engineering, this book is indispensable to those working in these fields. In addition there is much of direct interest to those concerned with metallurgy and inorganic chemistry.

The book is divided into four parts, with chapters as follows:

Part A. Theory: I. On the properties and the origin of magnetic fields in matter. II. Theory of ferromagnetism. III. Ferrimagnetism. IV. Magnetic anisotropies. V. Magnetization processes. VI. Dynamics of magnetization processes.

Part B. Measurements: VII. Methods of measuring ferromagnetic properties.

Part C. Intrinsic properties: VIII. Intrinsic properties of ferrites with spinel structure. IX. Intrinsic properties of ferrites with hexagonal crystal structure. X. Intrinsic properties of ferrites with garnet structure.

Part D. Polycrystalline ferrites: XI. Structure of polycrystalline ferrites. XII. Electrical properties. XIII. Static initial permeability. XIV. Frequency-dependence of the initial permeability. XV. Static hysteresis loops. XVI. Dynamic properties at high field strengths.

The book concludes with a list of references to the literature and an index.

French and German editions are in course of preparation.